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REVIBRATION OF RETARDED CONCRETE FOR CONTINUOUS BRIDGE DECKS

by
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conducted by
the Structural Research Laboratory
Department of Civil Engineering
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for the
National Cooperative Highway Research Program
Highway Research Board
National Academy of Sciences-National Research Council

Department of Civil Engineering

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Summary

Surveys of existing structures indicate that the deterioration of bridge deck concrete after exposure to freezing and thawing and de-icing agents often can be attributed to the formation of transverse cracks in the concrete. Such cracks may be formed or initiated already in the fresh concrete because of deflections of the formwork under the dead weight of the concrete or because of restraint of subsidence due to bleeding of the fresh concrete afforded by the top reinforcing steel.

Laboratory studies were conducted to investigate the effectiveness of revibration of concrete in repairing cracks several hours after it was placed. In addition the effect of revibration on concrete durability was investigated, and field experiments were conducted to verify the results from the laboratory tests and to investigate the feasibility of revibration in bridge deck construction.

The laboratory tests showed that surface revibration with a vibrating screed is an effective method to close flexural cracks on the concrete surface as well as horizontal cracks at the level of the top reinforcement and internal cracks up to a depth of at least 4 in. from the concrete surface. Revibration could be conducted successfully in the laboratory as long as the penetration resistance of the concrete according to ASTM C 403-68 did not exceed a value of 60 psi. Most concretes will reach this value approximately one-half to one hour prior to initial set. If properly conducted, surface revibration results in a smooth concrete surface so that no additional finishing after surface revibration except belting and brooming is required. Compressive strength and abrasion resistance of concrete were little affected by revibration. However, after surface revibration a slight increase of the spacing factor of air voids close to the concrete

surface was observed.

Accelerated freezing and thawing tests on concrete surfaces exposed to de-icing chemicals showed no significant difference in surface scaling of revibrated and non-revibrated concrete. However, it is likely though not proven in laboratory experiments that surface revibration will improve the resistance of concrete against surface spalling.

Portions of three bridge decks were revibrated approximately two hours after placing the concrete. It was shown that the entire width of a bridge deck can be revibrated with a vibrating screed in a continuous operation. The screed should be designed such that its profile can be adjusted to match the profile of the deck prior to revibration. In addition provisions should be made that during revibration the screed does not float freely on the concrete surface. Under these conditions surface revibration of bridge decks can be conducted successfully and no extensive finishing after revibration is required.

1. Introduction and Research Approach

1.1 Statement of the Problem

The deterioration of reinforced concrete bridge decks has been of much concern to highway engineers, researchers, and administrators throughout the United States. The frequent repairs of bridge decks which are necessary particularly in urban areas with heavy traffic and in regions with more severe climatic conditions are costly. The public inconvenience because of temporary closing of highways is of equal concern.

Several surveys of deteriorated bridge decks in various parts of the U. S. (1, 2, 3 and 4)* have been conducted during recent years. Various research programs on this subject have been carried out or are presently under way. A detailed literature review is given e.g. in (5). No single type or cause of bridge deck deterioration could be established from the surveys and research studies. However, spalling of the concrete surface and deterioration starting from transverse cracks in the bridge decks were the most common types of deterioration.

In most cases concrete deterioration may be traced back to one of the following causes:

(a) use of unsound ingredients in the concrete mix,

(b) inadequate air void system of the surface mortar of the bridge deck,

(c) transverse cracking at locations of transverse reinforcement.

An inadequate air voids system of the surface mortar may e.g. be caused by too low an initial air content of the concrete mix. Over finishing, sprinkling of water on the surface during the finishing process or late finishing may have similar effects.

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*Numbers in parentheses refer to entries in the list of references.

Cracking of the bridge deck may cause concrete deterioration since water can easily penetrate the crack and resaturate the adjacent concrete. More important, however, is the fact that moisture may penetrate through the cracks to the top reinforcement. Particularly when de-icing salts are used the reinforcement may corrode. Because of the expansive nature of the corrosion products the concrete cover will be subjected to high stresses in planes parallel to the concrete surface. These stresses may eventually lead to the propagation of horizontal cracks and subsequent spalling of the concrete cover.(5)

The formation of transverse cracks in bridge decks may be attributed to a variety of causes. They may be the result of flexural stresses due to the dead weight or vehicle loading in the negative moment region of continuous bridge decks. It is generally assumed, however, that such load induced transverse cracks occur comparatively infrequently.(5) Shrinkage of the hardened concrete may contribute to transverse cracking. However, the formation of cracks while the concrete still is in a plastic state seems to be of more importance:

(a) Early shrinkage of the cement paste is restrained by aggregates or steel reinforcement resulting in tensile stresses and subsequent cracking of the fresh concrete.

(b) Deflections and rotations of the formwork or of the supporting structure of the bridge deck due to the dead weight of concrete may cause stresses in fresh concrete. In the case of continuous concrete decks tensile stresses develop in the top fibers near the supports which may lead to transverse cracking.

(c) The top reinforcing steel may cause restraint to subsidence due to bleeding of the fresh concrete particularly in deeper slabs. Such restraint may result in the formation of horizontal plane of weakness zones or cracks as well as vertical cracks extending from the top reinforcement to the surface of the concrete bridge decks. Formation of planes of weakness may be enhanced by surface crusting which is likely to occur at high temperatures and wind velocities during casting.

1.2 Objective

It has been suggested that cracks which develop in the fresh concrete due mainly to formwork deflection but also due to restraint of subsidence may be repaired by revibrating the concrete after most of the bridge deck has been cast. It was hoped that such revibration may significantly improve the durability of reinforced bridge decks. Since revibration should be carried out after most of the concrete in a certain segment of the structure has been placed the use of retarded concrete would be essential to make revibration effective and to minimize the required revibration energy.

This investigation had the main objective to study the feasibility of this suggested construction practice.

1.3 Research Approach

Phase 1 of this study was a survey of current engineering practices regarding revibration or delayed vibration of bridge deck concrete. Forty-nine highway departments in the United States and six highway departments in Canada have responded.

Phase 2 was a laboratory study to investigate the effectiveness of revibration in closing cracks in reinforced concrete slabs while the concrete is in the plastic state. Reinforced concrete slabs 8 ft long, 3 ft wide and 6 in. thick were cast in flexible formwork with retarded and air entrained concrete. The slabs were deflected upwards between two and four and one-half hours after mixing in order to develop cracks on the surface of the specimens. The procedures necessary to develop cracks in the fresh concrete were investigated in a series of pilot tests. Some time after deflection the concrete was revibrated either by means of a surface screed or of an internal vibrator. Both the time of revibration and the energy level of revibration were varied. In order to evaluate the effectiveness of a certain revibration procedure several hardened concrete slabs were sawed into three segments, and then the sawed sections were carefully inspected to detect width and depth of cracks in the concrete. The type and extent of initial cracking, percentage of reinforcement, the amount of retarder and the curing conditions prior to revibration were also investigated. Seventy-nine test slabs were studied within this phase of the investigation.

Phase 3 was a study of the effect of revibration on bridge deck surface durability. In Phase 3a the effect of revibration on the general freeze-thaw characteristics of revibrated concrete was investigated using specimens 2 ft by 2 ft by 6 in. which were initially compacted and later revibrated on a vibrating table. Age at revibration, revibration energy level, presence of reinforcement, air content, and amount of retarder were the principle variables in this study. Twenty-one days after casting, the surfaces of the specimens were exposed to de-icing chemicals and subjected to cyclic freezing and thawing. Visual ratings of deterioration were conducted in accordance with procedures developed in previous research studies.(5, 6)

The results obtained from Phase 2 and Phase 3a were used to select the parameters to be studied on 21 large slabs of Phase 3b. Specimens 8 ft long 3 ft wide and 6 in. thick were revibrated with a surface screed. The principle parameters were type and extent of initial cracking, age of concrete at the time of revibration, revibration energy level, amount of retarder, air content of the concrete, and finishing procedures.

In Phase 4 the results obtained in the previous phases of this investigation were evaluated to develop recommendations for the use of revibration in the construction of concrete bridge decks including considerations regarding equipment and concrete properties. The feasibility of the recommended construction practice and the long time performance of revibrated reinforced concrete bridge deck were studied by revibrating three bridge decks under construction in the states of Illinois and Kansas. A supplementary report on the long time performance of these decks will be prepared at a later date.

In order to be able to describe the physical properties of the concrete which may influence its freeze-thaw durability the following tests were conducted for most parts of this investigation:

(a) cylinder tests for compressive strength (ASTM C 39-61)

(b) modified point count for air void parameters (ASTM C 457-66T)

(c) pressure test for air content of the fresh concrete (ASTM C 457-66T)

(d) time of initial and final set of the fresh concrete (ASTM C 403-68)

(e) acceleration measurements in the fresh concrete during revibration

(f) determination of density of revibrated and non-revibrated concrete

(g) pulse velocity measurements in revibrated and non-revibrated concrete

(h) freeze-thaw tests on prisms 3 by 3 by 15 in.

(i) determination of abrasion resistance (ASTM C 418-68)

Air entrained, retarded concrete was used for most laboratory experiments. The concrete had a water cement ratio of 0.64 by weight, a slump of 2 to 4 in., an air content between 5.5 and 6.5 percent and a maximum aggregate size of 1 in. Its compressive strength after 28 days was approximately 5500 psi. The initial set of the retarded concrete ranged from 6 hours 30 minutes to 8 hours, while the non-retarded concrete had an initial set of approximately 3 hours and 45 minutes.

1.4 Outline of Report

Chapter 2 summarizes the results obtained in this investigation. An interpretation of the findings, the conclusions to be drawn as well as suggestions for future research are given in Chapters 3 and 4.

Appendix A gives a review of related research. The survey on the use of revibration in the construction of reinforced concrete bridge decks is described in Appendix B. Detailed descriptions of experimental procedures and data are presented in Appendix C (Phase 2), D (Phase 3) and E (Phase 4). Additional experimental data are given in Appendix F. The original project statement prepared by NCHRP is given in Appendix G.

2. Findings

2.1 Survey of the Use of Revibration in the Construction of Reinforced Concrete Bridge Decks (Phase 1)

Letters of inquiry shown in Fig. B1* were sent to the highway departments of the 50 states of the U. S. and the District of Columbia as well as to 10 provinces of Canada. The replies from 48 states, the District of Columbia and 6 provinces of Canada are summarized in Table B1. No known cases of the use of revibration of retarded concrete bridge decks were reported. One structure was described on which delayed vibration of retarded concrete had been employed. Six Highway Departments noted that their specifications did not permit the use of delayed vibration or revibration, and 2 highway departments specifically stated that such procedures were not being considered. Two agencies indicated that retarded concrete was frequently used for bridge decks of continuous structures in order to allow dead load deflections to occur before the initial set of the concrete. Two cases of unintentional revibration of concrete bridge decks were reported, however, no unusual effects have been noted in either case. Apparently no experience in the use of revibration of bridge deck concrete existed prior to this investigation.

* Tables and figures are numbered consecutively throughout this report. The letter preceeding the number designates the Appendix in which the table or the figure is discussed in detail. All tables and figures are presented at the end of this report.

2.2 Development of Cracks in Fresh Concrete (Phase 2)

In order to develop cracks in the concrete prior to revibration the concrete was cast in flexible formwork as shown in Fig. C2 and was deflected upwards between 2 and 4 1/2 hours after mixing. Deflection was continued until either slight, medium or severe cracking was visible at the surface of the slabs. Cracks with a width of 1 to 2 x 10^{-3} in. and spaced between 5 and 10 in. apart were defined as slight cracking. A concrete curvature of approximately 5 x 10^{-4} in.$^{-1}$ was required to develop such cracks. Severe cracking corresponded to a crack width of 30 to 50 x 10^{-3} in. at a spacing of 1 to 2 in. and occurred at a curvature of approximately 2.5 x 10^{-3} in.$^{-1}$. The cracks were concentrated near transverse reinforcing bars and extended over the entire width of the slab. Variations in the time after mixing at which the concrete was deflected between 2 and 4 1/2 hours had little effect on crack width and crack spacing (Fig. C8). The cracks were shallow, and only a few cracks penetrated beyond the level of the top reinforcement (Fig. C10). Deflection of the concrete after 4 1/2 hours resulted in deeper cracks as shown in Fig. C11. However, spacing and maximum crack width did not significantly deviate from the values observed on specimens which were deflected earlier. In addition to the surface cracks, deflection resulted in the formation of internal cracks near transverse reinforcing bars (Fig. Clo and C11).

Under the normal laboratory environment no significant shrinkage cracking could be observed prior to or after initial set. Only in the case of severe drying conditions (high wind and temperatures of 95 or 110 F) shrinkage cracks penetrating beyond the level of the top reinforcement were developed (Fig.C23). Subsidence cracking or the formation of planes of weakness with an increased porosity at the level of the top reinforcement could not be found either under regular laboratory conditions or under the simulated wind and high temperature conditions. Artificial planes of weakness cracks were generated, however, by lifting the top reinforcement of the slabs two hours after mixing (Fig. C12).

2.3 Effectiveness of Revibration in Closing Cracks in Fresh Concrete (Phase 2)

Internal revibration proved to be an inefficient and ineffective method to close crack in fresh concrete even if conducted several hours prior to the initial set of the concrete (F9g. C13). Experiments in which the concrete was revibrated with a surface screed were considerably more successful. Therefore, surface revibration was used in most experiments. The surface screed consisted of an electrically powered vibrator mounted on a channel 8 in. wide as shown in Fig. C6. A frequency of 3200 cpm and a speed of forward motion of the screed of 8 sec per ft. were kept constant in all tests. These values were chosen because they resulted in the smoothest surface of the concrete after revibration. A centrifugal force of the vibrator of 720 lbs corresponding to 80 percent of the maximum output of the vibrator was defined as "high revibration energy level." At the "low energy level" the centrifugal force of the vibrator was 180 lbs or 20 percent of the maximum.

At a high energy level surface revibration was at least partially successful when conducted one hour or more before the initial set of the concrete. The penetration resistance of the fresh concrete according to ASTM C403-68 proved to be a useful parameter to determine the time after mixing at which revibration may be conducted successfully. At the high energy level most cracks may be repaired as long as the penetration resistance of the concrete is below 60 psi. A penetration resistance of 30 psi is the limit for the low energy level employed in this investigation (See Fig. C20). Because of the lack of a suitable method to measure and evaluate vibration energy in fresh concrete it is difficult to give a specific required minimum revibration energy. However, the experience gained during this investigation indicates that a revibration energy level which is sufficient to drive a slight moisture film to the entire concrete surface is also sufficient to close most cracks.

Variations of the layout of the top reinforcement or of the concrete cover had no apparent influence upon the effectiveness of revibration (Figs. C22). The maximum penetration resistance at which concrete may be surface revibrated is indipendent of the time of initial set or the amount of retarder in the concrete.

The concrete surface after revibration was in most instances sufficiently smooth so that no additional finishing after revibration except brooming was required. However, the experiments indicated that a better finish was obtained when the vibrator was mounted on the screed such that the plane of rotation of the vibrator was perpendicular to the direction of forward movement of the screed.

Since surface revibration penetrates 2 to 4 in. from the surface of the concrete, revibration was equally effective in closing plane of weakness cracks (Fig. C16).

Surface revibration at the high energy level closes early shrinkage cracks and can improve moderately crusted concrete surfaces. However, too low a revibration energy level may lead to the formation of additional, closely spaced surface cracks (Figs. C23). In all cases of moderate or severe crusting, however, extensive additional finishing after revibration was required.

2.4 Influence of Revibration on Strength and Air Void Characteristics of Concrete (Phase 2 and 3)

Revibration had no statistically significant effect on the compressive strength of retarded concrete (Fig. C24). The compressive strength of the non-retarded concrete however was slightly improved. These data were confirmed by measurements of sound velocity through the thickness of revibrated and non-revibrated slabs. No significant variations in either the dynamic modulus or the unit weight of revibrated and non-revibrated concrete were observed (Table C5).

Surface revibration had no pronounced effect upon the abrasion resistance of concrete (Table D10).

The effects of revibration on the air void characteristics of concrete are shown in Figs. C25 and Tables C6 and C7. The hand finishing procedures prior to revibration resultsed in all instances in a reduction of the air content and in an increase of the paste content of the surface layers of the concrete. However, the variations of the spacing factor over the thickness of the concrete were small. Surface revibration resulted in an increase of the spacing factor close to the concrete surface from an average value of 0.0070 in. prior to revibration to 0.0077 in. after revibration. Surface revibration had no measurable effect on the air void system of the concrete at a distance of more than 1 in. from the surface.

No significant effect of external revibration with a vibrating table on the air void characteristics and the paste content of concrete could be found (Tables C7).

2.5 Influence of Revibration on the Durability Characteristics of Uncracked Concrete (Phase 3a)

Plain and reinforced concrete specimens were revibrated on a vibrating table between 2 and 5 hours after mixing and for periods ranging from 10 to 40 seconds. No statistically significant difference between the surface durability of revibrated and non-revibrated concrete could be found although the revibrated concrete was generally slightly more durable than the non-revibrated concrete (Figs. D33 and D34).

A comparison of the durability of retarded and non-retarded concrete showed that the non-retarded concrete was significantly more durable than the retarded concrete (Fig. D36). Also, plain concrete specimens were more frost resistant than reinforced specimens (Fig. D37). It should be noted that the average spacing factor of retarded concrete was 0.0072 in. while non-retarded concrete other parameters being equal had a spacing factor of 0.0061 in. (Tables C7). Surface scaling was in all instances the only type of surface deterioration.

2.6 Influence of Revibration on the Durability of Cracked Concrete Slabs (Phase 3b)

The average surface deterioration ratings of cracked concrete slabs which were not revibrated are shown in Fig. D39. There was no clear indication that surface cracking or horizontal plane of weakness cracking results in reduced durability of the concrete surface when exposed to accelerated freezing and thawing in the laboratory. Only uniformly distributed scaling was observed and no surface spalls developed during freezing and thawing. Scaling of the cracked slabs was slightly more pronounced in the vicinity of the cracks. Uniform scaling was found in uncracked or revibrated slabs. (Figs. D41).

Surface revibration had no detrimental effect upon surface durability of the concrete as shown in Fig. D40. Generally the revibrated slabs were more frost resistant than the unrevibrated specimens. A statistical evaluation showed, however, that the difference between the average of all revibrated and all non-revibrated slabs is not statistically significant.

Similar to the results from tests on uncracked slabs the non-retarded concrete was considerably more frost resistant than the retarded concrete (Fig. D43). Since the compressive strength of the retarded concrete was between 15 and 50 percent higher than that of the non-retarded concrete, the air content of the retarded concrete could be increased from 6 to 8 percent resulting in a concrete as durable as the non-retarded concrete and with a compressive strength still higher than that of the non-retarded concrete (See Fig. D44).

Surface revibration resulted in an acceptable finish of the concrete, and hand finishing prior to revibration may not be necessary. It was hoped that elimination of hand finishing prior to revibration may offset the possible loss of air during surface revibration and thus improve surface durability. The data shown in Fig. D45 indicate, however, that hand finishing prior to revibration had little influence on the surface durability of revibrated or non-revibrated specimens. Late finishing of non-revibrated concrete resulted in a slight increase of the surface deterioration of the concrete. Additional finishing of concrete after revibration, however, had no significant effect upon concrete surface durability.

2.7 Field Applications

In order to investigate the feasilibity of revibration of bridge deck concrete in the field as well as to observe its long time performance, portions of three bridge decks under construction in Illinois and Kansas were revibrated. On the basis of the laboratory experiments the following guide lines for the field experiments were chosen:

(a) The bridge deck concrete shall be revibrated with a vibrating screed when the penetration resistance of the concrete reaches approximately 25 psi.

(b) The bridge deck concrete shall be finished prior to vibration and additional finishing after revibration shall be kept to a minimum.

(c) No particular requirements regarding concrete mix proportions in addition to those developed by the respective highway department will be made.

The use of set retarding admixtures is desirable but not mandatory.

On July 10, 1969, portions of the deck of a noncomposite, skewed and continuous span bridge with structural steel I beams near Champaign, Illinois, was revibrated (Fig. E46). The revibrated section of the bridge deck was adjacent to the safety curb and was 3 ft 3 in. wide extending 15 ft in both directions from the center support of the bridge. A longitudinal construction joint separated the curb areas from the center part of the deck which had been cast several days earlier. The vibrating screed which was used in the laboratory experiments was also employed for the revibration of the bridge deck. The retarded concrete had an air content of 4 to 5 percent, a slump of 2 1/2 in. and an initial set two hrs. 40 min. after casting. The air temperature during casting ranged from 84 to 89 F, the relative humidity was around 65 percent, and the day was sunny with only slight westerly winds. Revibration was conducted at the low energy level defined in Section 2.3 approximately two hours after placing the concrete. At that time a concrete sample which was kept moist until testing and which was taken from the same batch as the bridge deck concrete had a penetration resistance of approximately 25 psi. Revibration appeared to be effective since a thin moisture film covering most of the concrete surface was developed during revibration. However, finishing after revibration was necessary in order to obtain a continuous transition from the revibrated sections across the longitudinal joint to the adjacent hardened concrete of the main deck. Since at that time the concrete had almost reached its initial set finishing was difficult, and the experiment showed clearly that finishing after revibration should be avoided whenever possible. The revibrated sections were inspected several times after casting. So far no apparent differences between the vibrated and the non-revibrated portions of the deck could be detected. The visual observations of the deck will be continued throughout the coming years.

On August 27, 1969 a section of a continuous, noncomposite bridge with welded steel plate girders near Newton, Kansas, was revibrated (Fig. E49). The revibrated area extended over the entire width of the deck from one abutment over a length of 82 ft. A free floating vibrating screed which was supported only by the fresh concrete was used. A vibrator with a frequency of 3200 cpm vibrating parallel to the direction of the forward movement of the screed was mounted in the center of the screed (Fig. E50). The bridge deck concrete was non-retarded and had an air content between 5 and 7 percent and a slump from 1 1/2 to 3 in. The initial set of the concrete was approximately 2 hr 50 min. During most of the construction period the sky was overcast with temperatures ranging from 72 to 78 F and light winds. Prior to revibration the concrete was finished with a regular finishing machine. Immediately after finishing a water emulsion of aliphatic alcohols was sprayed on the concrete surface resulting in a monomolecular film which retards evaporation of bleeding water.(24) Approximately 1 1/2 hours after casting revibration was commenced. At that time the penetration resistance of a control sample of concrete which had been kept moist until testing was approximately 25 psi. Two major problems were encountered in this field experiment. Since the vibrator was free floating it had a tendency to sink slightly into the fresh concrete. Furthermore, the shape of the vibrating screed did not precisely match the profile of the bridge deck surface so that the screed did not always touch the entire concrete surface. Therefore, portions of the bridge deck particularly in the center of the deck were not revibrated. Each time the forward movement of the vibrating screed was stopped the vibrator left a noticeable mark in the bridge deck surface (Fig. E51). Because of these deficiencies rather extensive and cumbersome finishing after revibration was required. Finishing was particularly difficult since at that time the concrete had approached its initial set.

Based upon the experience of the previous field experiments a new vibrating screed was constructed and was used to revibrate a similar bridge deck near Newton, Kansas, on September 23, 1969. A vibrating pan with two small vibrators attached to the pan at about its third points was mounted to the frame of a finishing machine as shown in Fig. E52. The equipment was supported by rails adjacent to the safety curbs of the bridge deck. The shape of the vibrating pan could be adjusted so that it closely matched the original provile of the bridge deck surface. The bridge deck concrete contained a set retarder and had an air content between 4 and 5.5 percent and a slump ranging from 2 to 4 in. The initial set of the concrete occurred 3 hrs 30 min after placing the deck. The deck was finished immediately after casting and parts of the concrete surface were sprayed with the water-alcohol emulsion. Sunny skies with temperatures ranging from 70 to 80 F and moderate winds prevailed during most of the day. Approximately 2 1/2 hours after casting, when a control sample which had the same exposure as the bridge deck surface reached a penetration resistance of 28 psi, revibration of the bridge deck was commenced and continued over the entire width of the deck over a length of approximately 133 ft. The field experiment was successful. Revibration resulted in a smooth concrete surface (Fig. E53), and in most cases no additional finishing except belting and brooming was required after revibration. In a few instances, however, revibration caused closely spaced surface cracks (Fig. E54). These cracks had an appearance similar to the cracks which were observed in the laboratory after revibration of surface crusted concrete. It is likely that the revibration energy level in the field experiment was insufficient to break up the entire surface crust. Such cracks were not observed in areas which had been sprayed with the water-alcohol emulsion immediately after finishing.

Cores have been taken from both bridges in Kansas. They will be used to compare the air void characteristics of revibrated and non-revibrated concrete. These results will be reported at a later date together with observations of the long time performance of the revibrated decks.

3. Interpretation

The major emphasis of this investigation was placed upon studies of the effectiveness of revibration in closing transverse cracks in reinforced concrete bridge decks which may have been formed as a consequence of formwork deflections due to the dead weight of the fresh concrete. The experimental data showed, however, that in order to develop substantial cracking in fresh concrete several hours before initial set a curvature of the concrete surface in excess of 0.001 $in.^{-1}$ was required. Unless the concrete had a penetration resistance of more than 15 psi at the time of deflection the cracks were shallow and hardly penetrated beyond the surface regions of the concrete. It became apparent that during the first hours after mixing the fresh concrete used in this investigation could develop considerable plastic deformations without cracking or that the fluidity of the concrete was sufficient so that microcracks were healed soon after their formation. More severe surface cracking may develop if deflections occur after the penetration resistance of the concrete exceeds 15 psi or when severe surface crusting has occurred. Such conditions may develop several hours before initial set of retarded concrete while the concrete is still sufficiently plastic to be revibrated.

The formation of planes or zones of weakness at the level of the top reinforcement could not be observed in the laboratory even under the extreme environmental conditions of elevated temperatures and high winds. Nevertheless, planes of weakness formation has been observed in a number of instances in the field and can be a major cause of bridge deck deterioration. It is likely that the laboratory conditions still were too favorable for the formation of planes or zones of weakness. Deeper specimens, concrete with a higher slump and water content, and concrete ingredients which lead to a higher bleeding rate of the concrete may in fact have produced planes of weakness even in laboratory specimens. However, no information exists on the time after casting at which such planes of weakness may develop.

Independent of the cause of cracking, revibration is an effective and economically feasible method to close surface cracks, internal cracks or planes of weakness cracks in the fresh concrete as long as the penetration resistance of the concrete is not in excess of 60 psi. This condition is reached between 1/2 and 1 hr prior to initial set. If the energy level is chosen such that revibration results in the formation of a moisture film over the entire concrete surface no significant additional finishing after revibration is required. A substantial number of cracks may be closed by revibration at a high energy level even if the concrete is close to its initial set at the time of revibration. Then, however, surface revibration may be non-uniform and additional finishing may be required, which is very difficult to perform at such a late state. It is possible that revibration prior to initial set even of uncracked concrete may cause the relief of residual stresses due to early shrinkage and bleeding and thus may reduce the cracking tendency of the hardened concrete. Since flexural cracking due to formwork deflection can be substantially reduced by the use of retarders it appears that revibration is more important to prevent and repair planes of weakness than it is to repair flexural cracks on the concrete surface.

The laboratory experiments showed no significant difference between the surface scaling resistance of revibrated and non-revibrated concrete. It has to be pointed out, however, that scaling is only one type of surface deterioration of concrete in the field. Spalling of the concrete surface may be the more severe form of deterioration and has been frequently observed in actual bridge decks. The development of surface spalls often is connected with corrosion of the reinforcement and thus depends on the total time of exposure of the concrete to low temperatures. Therefore, the results of comparatively short accelerated laboratory tests are in most cases no indication of the spalling resistance of a concrete surface. Since the experiments showed that surface revibration is an effective way to close horizontal plane of weakness cracks as long as they are formed or initiated prior to initial set it is likely that, though not proven in the laboratory, revibration may indeed improve the frost resistance of bridge decks in cases where surface spalling is the dominant form of deterioration.

The differences in the scaling resistance between retarded and non-retarded concrete can with all likelihood be attributed to influences of the particular retarder on the air void characteristics of the concrete. Since adjustments of the total air content of the retarded concrete resulted in a concrete as durable as non-retarded concrete, there is no indication that retarders may necessarily impare concrete durability. However, the period of time during which bleeding occurs may be longer for retarded concrete than it is for non-retarded concrete, thus increasing the crusting tendency of retarded concrete. The application of surface sprays as barriers against excessive moisture evaporation may, however, significantly reduce the danger of crusting as has been shown in the field experiments.

The feasibility of revibration of bridge deck concrete in the field has been demonstrated particularly by the second experiment conducted in Kansas. Surface revibration of the entire width of the deck in one operation appears to be the most practical approach. Provisions have to be made, however, to adjust the revibration energy level as well as the shape of the vibrating pan, and to support the surface vibrator so that it does not float freely on the concrete surface. In determining the time of revibration it proved to be advantageous to use the penetration resistance of a sample which is subjected to the same exposure conditions as the bridge deck surface. Batch to batch variation of the concrete in the deck require close observation of the particular concrete properties and may necessitate changes in revibration energy as well as in the speed of forward movement of the revibration equipment during the operation.

4. Conclusions and Suggested Research

The conclusions to be drawn from this research can be summarized as follows:

1. For the types of concrete studied in this investigation, and formwork deflections occurring within 4 1/2 hours after mixing, significant surface cracking of the concrete was developed only if the deflections caused a curvature of the surface in excess of 0.001 $in.^{-1}$.

2. Exposure of the fresh concrete to high winds and temperatures above 95 F resulted in surface crusting and shrinkage cracks. However, reinforced concrete slabs 6 in. deep, with a concrete cover above the reinforcement of 1 1/2 in. and made from concrete with a low bleeding rate did

not show planes of weakness at the level of the top reinforcement after exposure to heat and wind.

3. Internal vibration is an inefficient and impractical method to revibrate concrete bridge decks. Surface revibration, however, can be effectively employed to repair surface cracks, horizontal cracks at the level of the top reinforcement and internal cracks up to a depth of at least 4 in. from the concrete surface. Surface revibration may be successful if conducted before the concrete reaches a penetration resistance of 60 psi. Most concretes will reach this value between one-half and one hour prior to initial set. The required revibration energy is sufficient as long as revibration results in the development of a thin moisture film on the entire concrete surface.

4. No additional finishing of the concrete except belting or brooming is required after sufficient surface revibration of a concrete with a penetration resistance of less than 60 psi.

5. Surface revibration at a high energy level may improve moderately crusted concrete surfaces. However, insufficient revibration of severely crusted surfaces may cause additional surface cracks.

6. Surface cracks had no measurable effect on the scaling resistance of the concrete. Revibration did not impare the scaling resistance of the concrete though the average spacing factor of the surface layers of the concrete was increased by revibration from 0.0070 to 0.0077 in.

7. Retarded concrete can be as durable as non-retarded concrete as long as the air void characteristics in both types of concrete are comparable. The use of retarders may lead to improved concrete durability since the period of time during which the concrete can be deflected without development of significant surface cracks can be increased by several hours. Retarders may,

however, lead to more severe crusting because of the increased period of time during which bleeding can occur. The use of surface sprays to prevent excessive moisture evaporation may counteract this disadvantage.

8. Surface revibration of reinforced concrete bridge decks in the field is feasible. The vibrating screed should have an adjustable profile and vibrators with variable vibration energy. The screed should be supported by rails or similar set-ups. The time at which revibration is commenced should be determined on the basis of the penetration resistance of a concrete sample which is subjected to the same exposure conditions as the bridge deck surface.

The investigation reported herein was hampered by the lack of knowledge in several areas, and the following additional information is required before final and conclusive recommendations regarding revibration of field concrete can be made:

(a) Spalling of the concrete surface associated with planes of weakness is recognized as a major type of bridge deck deterioration in the field. Revibration is a potential method to repair such planes of weakness if they have initiated prior to revibration. Nevertheless, planes of weakness in laboratory specimens could be generated only under extreme conditions. Therefore, the mechanism of plane of weakness cracking as well as the principal parameters controlling their formation need further clarification by laboratory experiments.

(b) Since spalling of the concrete surface is a type of deterioration seldom found in accelerated laboratory tests it is difficult to estimate reliably the durability of field concrete on the basis of laboratory investigations. The need for improved and more realistic laboratory procedures has been apparent for a long time.

(c) The time at which formwork deflections may cause significant flexural cracking in fresh concrete has not been sufficiently explored. Therefore, careful measurements of the extensibility of fresh concrete and the basic parameters effecting it such as age, curing conditions and fluidity of the concrete are needed.

(d) The effect of very high revibration frequencies has not been studied in this investigation. Such frequencies may, however, allow revibration after initial set and may also result in significant improvement of strength and density of the concrete.

(e) The field experiments showed the feasibility of revibration of bridge decks. The equipment used, however, was crude and further development of equipment and construction procedures is encouraged.

5. List of References

1. Durability of Concrete Bridge Decks, A Cooperative Study, Report 1, State Highway Commission of Kansas, U. S. Bureau of Public Roads, Portland Cement Association, 1965.

2. Durability of Concrete Bridge Decks, A Cooperative Study, Report 2, Michigan State Highway Department, U. S. Bureau of Public Roads, Portland Cement Association, 1965.

3. Durability of Concrete Bridge Decks, A Cooperative Study, Report 3, California Division of Highways, U. S. Bureau of Public Roads, Portland Cement Association, 1967.

4. Durability of Concrete Bridge Decks, A Cooperative Study, Report 4, Missouri State Highway Department, U. S. Bureau of Public Roads, Portland Cement Association, 1969.

5. J. P. Callahan, C. P. Siess, C. E. Kesler, "Effect of Stress on Freeze-Thaw Durability of Concrete Bridge Decks," Department of Theoretical and Applied Mechanics Report No. 678, University of Illinois, Urbana, Illinois, June 1968.

6. W. R. Malisch, D. A. Raecke; D. M. Fischer; J. L. Lott, T. W. Kennedy, C. E. Kesler, "Physical Factors Influencing Resistance of Concrete to Deicing Agents," National Cooperative Highway Research Program Report No. 27, Highway Research Board, 1966.

7. W. A. Cordon, "Freezing and Thawing of Concrete: Mechanisms and Control," Monograph No. 3, American Concrete Institute, 1966.

8. Bridge Deck Deterioration Study, Part 7; Weathering Test of Reinforced Concrete Slab with Various Depths of Steel; State Highway Commission of Kansas, Planning and Research Department, 1968.

9. Bridge Deck Deterioration Study, Part 8, Special Study of Blue Rapids Bridge Deck; State Highway Commission of Kansas, Planning and Research Department, 1969.

10. Ryell, J., "An Unusual Case of Surface Deterioration on a Concrete Bridge Deck," Proceedings, American Concrete Institute, Vol. 62, April, 1965, pp. 421-442.

11. R. N. Wright, W. H. Walker, "Criteria for the Deflection of Steel Bridges," Paper presented at the 1969 Regional Meetings of the AASHO Committee on Bridges and Structures.

12. Meyer, E. V., "Concrete exposed to vibration or shock during the entire setting period," Betonteknik XI, Nr. 4, Stockholm 1955.

13. Sawyer, D. H., Lee, S. F., "The effects of revibration on properties of portland cement concrete," Proceedings ASTM Vol. 56, 1956, pp. 1215-1227.

14. Vollick, C. A., "Effects of revibrating concrete," Proceedings, ACI Journal Vol. 54, 1958, pp.

15. Mattison, E. N., "Delayed screeding of concrete," Constructional Review Vol. 32, Nr. 7, July 1959, pp. 30.

16. Mattison, E. N., "Some experiments with delayed and repeated vibration of concrete," Constructional Review Vol. 32, Nr. 7, Sept. 1959, pp. 29-33.

17. Walz, K., "Vibrated Concrete," Verlag Wilhelm Ernst und Sohn, Berlin 1960 (in German).

18. Hansen, T. C., "Creep and stress relaxation of concrete," Svenska Forskningsinstitutet foer Cement och Betong vid Kungl. Tekniska Hoegskolan i. Stockholm, Handlingar Nr. 31, Stockholm 1960.

19. Buehrer R., "Railroad bridges in prestressed concrete," Proceedings Deutscher Ausschuss für Stahlbeton Vol. 112, second edition Berlin 1961 (in German).

20. Hilsdorf, H., Finsterwalder, K., "Investigation into the effect of revibration of concrete and of coatings on strength, shrinkage and creep of concrete," Proceedings Deutscher Auss chuss für Stahlbeton Vol. 184, Berlin 1966 (in German).

21. Schatz, R. J., "Setting Time of Concrete controlled by the use of admixtures," Proceedings, American Concrete Institute, Vol. 55, January 1959, pp. 769-781.

22. Ray, K., Karmakar, J. K., Datta, S. K., "Variation of concrete strength due to delayed placing," Indian Concrete Journal, Vol. 30, No. 2, Feb. 1956, p. 42.

23. C. Avram; N. Voina; O. Mirsu, "L'influence de la revibration sur les proprietes de la pate de ciment durcie et des betons," (The effect of revibration on the properties of cement paste and concrete) Revue des Materiaux de Construction, Ciments et Beton, No. 619, April 1967.

24. W. A. Cordon, J. D. Thorpe, "Control of Rapid Drying of Fresh Concrete by Evaporation Control," Preceedings, American Concrete Institute, Vol. 62, August 1965, pp. 977-985.

Appendix A
Review of Related Research

This appendix includes a summary of the results of the recently conducted bridge deck surveys (1-4). A more detailed discussion of freeze-thaw durability of concrete can be found e.g. in (5 or 7). The second part of Appendix A gives a discussion of research into the effect of revibration on concrete properties.

A.1 Bridge Deck Surveys

A thorough analysis of bridge deck survey data has been obtained from the cooperative survey recently conducted by the Division of Highways of the states of Kansas, Michigan, California and Missouri.(1 to 4; 8; 9) According to those surveys, scaling of the surface mortar, transverse cracking and subsequent surface spalling were the main types of deterioration.

Scaling was associated with freeze-thaw action and particularly with the use of de-icing agents and normally did not follow any particular pattern. Scaling can in most cases be attributed to one or more of the following causes: inadequate finishing practices such as excessive or too late finishing, insufficient air void system of the surface mortar, poor drainage of the bridge decks, and excessive use of de-icers. In addition, it was hypothesized (5) that differences in the thermal length change between the surface mortar and the coarse aggregate layers of the concrete may result in thermal stresses and as a consequence in surface scaling.

Transverse cracking, which was found to be more severe in continuous spans, may be due to vehicle loading, plastic or drying shrinkage, long time volume changes, improper placement of the reinforcing bars, stresses due to formwork deflections or rotations or due to the removal of formwork in continuous reinforced concrete bridge decks, and resistance to subsidence of concrete during the bleeding period by the rigidly held top reinforcement. Resistance to subsidence not only causes transverse cracks, but it may lead also to the formation of "planes of weakness" at the level of the top reinforcement. At such planes the porosity of the cement paste is increased and horizontal cracking may occur. Early crusting of the concrete surface may enhance the formation of planes of weakness. An increased concrete cover does not necessarily prevent the formation of horizontal cracks but may delay the occurrence of subsequent spalling.(8; 9; 10)

Transverse cracks are not necessarily concentrated in the negative moment regions of continuous bridges, and no clear correlation between transverse cracking and flexibility of supporting steel stringers seems to exist.(11) This observation underlines the significance of early shrinkage and restraint of subsidence as major causes of transverse cracking.

In the bridge deck surveys surface spalling was attributed mainly to the following causes: resistance to subsidence of concrete as described above, early drying shrinkage and crusting of the concrete surface, and corrosion of reinforcement in the vicinity of transverse cracks. Corrosion may be particularly dangerous where planes of weakness have been formed. It was found that surface spalling or fracture plane deterioration was significantly greater when the depth of the concrete cover above the top steel was only 1 1/2 in. or less. Traffic action and insufficient drainage of the bridge decks may accelerate surface spalling of inadequate concrete.

Recent laboratory investigations underline the detrimental effect of corrosion of the reinforcing bars at sections with transverse cracks.(5) However, adequate finishing procedures and concrete properties which insure sufficient air content of the surface mortar are considered equally important. It was found (5) that external stresses influence the rate of development of surface scaling only to a limited degree and stress does not seem to be a primary factor for the durability of bridge deck concrete.

Longitudinal cracking of bridge decks was found only in a few cases indicating that the bridge decks are in most cases adequately designed for life loading.

A.2 Effect of Revibration on the Properties of Plain Concrete

Revibration or delayed vibration of concrete is not a generally accepted construction procedure. It was hypothesized for a long time that concrete once it is placed, compacted and finished should not be disturbed until it gains sufficient initial strength. This, however, is an unrealistic viewpoint since concrete often is revibrated unintentionally by the initial vibration of subsequently cast concrete. Therefore, the effect of revibration upon some concrete properties has been studied in the past in a number of investigations. (12-23)

It is generally agreed that revibration of concrete between 2 and 6 hours after mixing may result in a 10 to 30 percent increase of the concrete compressive strength compared to the strength of non-revibrated concrete. This is true even for concrete which was initially compacted to an optimum density. It is assumed that this phenomenon is due to the closing of microcracks between paste and aggregates which are formed because of the restraint of early shrinkage of the cement paste. It also has been found that the total pore volume of revibrated concrete is slightly less than the pore volume of non-revibrated concrete. This increased density may be an additional reason for the improved strength characteristics of revibrated concrete. It has been suggested also that the structure of cement paste and possibly the hydration process may be influenced by revibration. (13; 22; 23) This agrees with the observation that even revibration of neat cement paste may result in strength increase between

5 and 20 percent of the strength of non-revibrated paste (20). Strength increases of the paste up to 130 percent were reported in (23). This unusually high strength increase was associated with a significant reduction of the water cement ratio during revibration.

The effect of revibration upon the tensile strength of concrete has not been clarified sufficiently. It was shown in two investigations (13; 20) that revibration has little influence upon the tensile strength of concrete. Apparently, this is contradictory to any of the concepts which were suggested to explain the increase of the compressive strength of concrete by revibration.

Revibration of concrete results in a slight increase of the modulus of elasticity, a slight reduction of shrinkage, but no significant change in the creep behavior of concrete (19; 20). However, also a marked reduction in creep of revibrated cement paste was reported in one case (23).

No detailed investigations on the effect of revibration on the bond strength between concrete and imbedded reinforcing bars could be found in the literature. However, it seems likely that, through a reduction of water pockets which may form under the reinforcement during bleeding, revibration may increase the bond strength.

The durability of concrete may be reduced by revibration if high revibration energies are used (13) mainly because of a reduction of the volume of entrained air. No information regarding the abrasion resistance of revibrated concrete could be found. However, it may be possible that increased bleeding of the concrete during revibration may weaken the surface mortar and reduce its abrasion resistance.

It is generally agreed upon that the effect of revibration increases as the revibration energy is increased (17; 19; 20).

The time after mixing at which concrete is revibrated has a major influence upon the effectiveness of revibration. Revibration only a few hours after mixing generally has little influence upon concrete properties and in one instance a slight reduction of the concrete compressive strength was observed (20). Revibration becomes more effective if it is conducted immediately before or after initial set. If revibration is delayed beyond the final set its effectiveness decreases and eventually becomes insignificant.

The influence of concrete mix design seems to be associated with the corresponding variations in setting time. The use of retarders may substantially increase the period of time during which revibration of concrete is beneficial (21).

Methods of revibration include the use of internal, external or surface vibrators. No information on the effect of revibration by means of surface vibrators could be found. Improved freezing and thawing resistance due to initial surface vibration was, however, reported in (6). The use of internal vibrators limits the time interval during which revibration may be conducted successfully. If the concrete is too stiff the vibrator may not sufficiently penetrate into the concrete. Segregation may occur with increased cement paste content in zones where the vibrator was inserted. External vibrators generally have been more effective in improving concrete properties but the practical application of external vibration apparently is limited by structural size.

Laboratory investigations showed that revibration is more effective if the specimen is revibrated while subjected to a small compressive stress. This procedure, however, has only limited application in actual construction practice.

Delayed vibration using an external vibrator may result in a strength increase of approximately 10 to 20 percent if carried out shortly after the initial set of the concrete (14). Further delay, however, may result in a severe reduction of concrete strength.

It may be generally concluded that revibration in most instances improves strength and deformation characteristics of concrete. However, revibration may have an adverse effect on the frost and abrasion resistance of concrete.

Appendix B
Survey of the Use of Revibration in the Construction of Reinforced Concrete Bridge Decks-Phase 1

Prior to this investigation Dr. Best of Kansas State University conducted an inquiry into the use of revibration in the construction of reinforced concrete bridge decks or pavements. Dr. Best was kind enough to make his information available for this investigation.

In this survey a letter of inquiry was sent to the highway departments of the fifty states and the District of Columbia and to ten provinces of Canada. The letter requested the highway departments to describe their experience in the use of delayed vibration or revibration of retarded concrete bridge decks. A sample letter of this inquiry is shown in Fig. B1.

The replies from 48 states, the District of Columbia and six provinces of Canada are summarized in Table B1. There were no known cases of the use of revibration of retarded concrete bridge decks and only one structure on which delayed vibration of retarded concrete was employed. Six highway departments noted that specifications did not permit the use of delayed vibration or revibration, and two highway departments specifically stated that such procedures were not being considered.

Two highway departments indicated that retarded concrete was frequently used for bridge decks of continuous structures in order to allow dead load deflections to occur before the initial set of the concrete occurs. However, neither delayed vibration nor revibration was employed. Two cases of unintentional revibration of concrete bridge decks were reported. No unusual effects have been noted in either case. The Department of Highways and Transportation of the province of Saskatchewan, Canada, mentioned the only use of delayed vibration of retarded concrete bridge decks. The work was done by a consulting firm for the municipal branch. The structure was a three-span continuous bridge with precast, prestressed girders and a cast in place deck. The continuous floor slab was placed in one operation using a retarder and delayed vibration. No additional data with regard to the long time performance of the bridge deck were provided.

The state of Kansas is aware of the possible usefulness of revibration and in fact intends to include revibration in construction specifications. However, no experience in regard to the feasibility of the use of revibration as well as with regard to the long time performance of revibrated decks was available at the time of the inquiry.

Appendix C
Effectiveness Study-Phase 2

C.1 Objective and Scope

The objective of this phase of the investigation was to study the effectiveness of revibration in closing cracks in fresh concrete. The following main test series were conducted:

Series 1: Method of revibration, revibration energy and extent of initial cracking.

Series 2: Time of revibration

Series 3: Percentage of reinforcement.

Series 4: Time of initial set.

Series 5: Curing conditions prior to revibration.

Series 7: Effectiveness of revibration in closing plane of weakness cracks.

Series 8: Effectiveness of revibration in closing cracks which have been generated at a higher age.

Series 9: Effect of direction of revibration.

Series 10: Influence of revibration on air content distribution and abrasion instance.

Originally a Series 6 was planned to study the influence of air content on effectiveness of revibration. This series, however, was considered of minor importance and, therefore, was omitted from the program. Studies on the effect of air content were, however, included in the durability studies (Phases 3a and 3b).

In addition to the main test series a pilot study (Series P) was conducted to determine methods to develop cracks in the slabs while the concrete was still plastic. The effect of revibration on concrete density and compressive strength was investigated in Series C. Accelerometer measurements were used to evaluate the depth to which the revibration energy may penetrate during surface revibration (Series ACC). A total of 79 large slabs was tested within Phase 2.

C.2 Description of Specimens

All specimens investigated within this phase consisted of reinforced concrete slabs 8 ft long, 3 ft wide and 6 in. thick. The specimens were cast in steel formwork as shown in Fig. C2. The bottom plate of the formwork had a thickness of 3/8 in. The longer sides of the form were laminated plates made up of individual steel bars 1 in. x 1/2 in. in cross section. Two teflon strips were placed between the indicidual bars, which were clamped together with bolts spaced 2 ft apart. The surface of the sides facing the concrete was covered with plastic sheeting. Laminated plates for the sides of the formwork insured high flexibility of the form which was required to develop severe flexural cracking in the fresh concrete. The formwork was supported by two concrete blocks and was tied to the test floor. The formwork and the concrete could be subjected to a negative moment by means of a hydraulic jack and load distributing girders. In order to prevent relative movement of the reinforcement during deflection of the formwork both top and bottom layers of the reinforcing bars were held to the bottom of the formwork by clamps and chairs as shown in Figs. C3a; C3b and C3c. Three sets of forms were available for this investigation.

Most of the specimens were reinforced with two layers of reinforcement consisting of #5 bars spaced at 6 in. longitudinally and #4 bars spaced at 9 in. laterally as shown in Fig. C3a. A concrete cover of 1 1/2 in. was held constant for most slabs except for some specimens of Series 3, "Percentage of Reinforcement." The layouts of reinforcement used in this series are shown in Figs. C3b and C3c.

The specimens tested in Phase 2 were designated by a sequence of numbers or letters: The first term described the method of revibration (SU for surface revibration and IN for internal revibration). The second number indicates the test series. The third term describes the extent of initial cracking (SL for slight cracking, ME for medium cracking , SE for severe cracking). The last term describes the extent of revibration energy (0 for no revibration, 20 for a low revibration energy and 80 for a high revibration energy). As an example, SU-2-SE-80 designated a specimen of Series 2 that was revibrated with a surface screed at an energy level of 80 percent and was severely cracked prior to revibration. In a number of instances additional terms were used to describe a particular specimen. Their description is given in Tables C2a through C2f in which the most significant data of all specimens tested within Phase 2 of this investigation are summarized.

C.3 Materials

Type 1 cement with an initial set of 3 hours 45 minutes and a final set of 5 hours 45 minutes after casting under laboratory conditions was used throughout this investigation. The coarse aggregate consisted of crushed limestone with a maximum size of 1 in. and was obtained from a quarry near Fairmount, Illinois. This particular aggregate had good service records. The fine aggregate was primarily quartz and is an outwash of the Wisconsin glaciation. The aggregate properties are summarized in Table C3.

1.2 fl oz per 100 lb of cement of a neutralized vinsol resin were used as an air entraining agent to produce an average air content as determined by the pressure method between 5 and 7 percent except in such cases where a lower air content was required. 4.5 fl oz of hydroxylated polymers per 100 lb of cement were used as retarder resulting in an initial set of the concrete approximately 7 to 8 hrs and a final set of approximately 9 hrs after mixing under laboratory conditions with a temperature of 72 F and a relative humidity of 50 percent. Typical results of a penetration test to determine final and initial set of the concrete are shown in Fig. C4.

Intermediate grade deformed bars conforming to ASTM designations A15-64 and A305-64 were used as reinforcement. The materials used in this investigation are approved by most State Highway Departments.

C.4 Concrete Mix Proportions

The following mix was used throughout this investigation:

Water: 300 lbs per cu yd

Cement: 467 lbs per cu yd

Coarse aggregates: 1500 lbs per cu yd; SSD

Fine aggregates: 1510 lbs per cy yd; SSD

These values correspond to a water cement retio of 0.65 and a cement factor of 5 bags per cy yd. The slump of the concrete ranged between 2 and 4 in. All aggregates were dried on a heated floor prior to casting.

C.5 Fabrication of Specimens

The mixing and casting procedures employed for all specimens were as follows: A 7.5 cu ft batch was mixed in a batch plant with a horizontal tub mixer. The dry ingredients were first mixed for one minute. Then some water containing the air entraining agent and an additional amount of water containing the retarder were added to the mix. The wet mixture was then mixed for four minutes. Then the concrete was placed in the formwork described in section C.2 and shown in Fig. C2. Two batches were required for each slab and one half of each slab was cast from one batch. The concrete was initially vibrated with an internal vibrator. After the excess concrete was struck off, the surface was hand finished with a magnesium trowel.

Compression test cylinders were cast for several batches of concrete to determine the 28-day strength. Time of initial and final set were determined for each batch from a penetration test in accordance with ASTM C 403-68.

All specimens were covered with a plastic sheet approximately 7 hrs after casting. Specimens which had to be tested in the hardened state were moist cured for a period of 7 days in a fog room and were then exposed to air drying at a relative humidity of approximately 50 percent and a temperature of 70 F. Specimens which were only used to determine cracking and effectiveness of revibration of fresh concrete received no curing treatment beyond the first day.

C.6 Test Procedures

C.6.1 Development of Cracks in Fresh Concrete

Between two and four and one half hours after mixing the concrete slabs and the formwork were deflected upwards by means of a hydraulic jack as shown in Fig. C2. The slabs were deflected in increments of approximately 3/8 in. After each increment the deflection was kept constant for a period of approximately two minutes. Deflection was continued until either slight, medium or severe cracking as defined below was developed. The deflection of the formwork was kept constant at the desired final value until the hardened concrete slabs were removed from the formwork. The extent of cracking was defined as follows:

Cracking	Maximum Crack Width in.	Average Crack Spacing in.	Midspan Deflection in.
slight	1 to 2 x 10^{-3}	5 to 10	0.5
medium	5 to 10 x 10^{-3}	2 to 3	2.0
severe	30 to 50 x 10^{-3}	1 to 2	3.5

After deflection, the surfaces of the slabs were inspected for cracks, the cracks were marked, and in some tests the crack width was measured by means of a microscope. A photograph of a deflected slab and formwork is shown in Fig. C5.

Initially the major emphasis was placed upon the study of the effectiveness of revibration in closing cracks which may have been caused by formwork deflections. However, during the course of this investigation it became apparent that revibration may be at least as significant as a means of repairing subsidence cracks. However, subsidence cracking or the formation of planes of weakness with an increased porosity could not be observed to any significant extent in the standard specimens. Nevertheless, it was desirable to investigate the effectiveness of revibration in closing plane of weakness cracks. Such cracks were, therefore, generated artificially by lifting the top reinforcement of the slabs some time after casting. For this 1/4 in. bolts were attached to the top reinforcement and protruded through the bottom plate of the formwork near the center of the slab. Horizontal cracks at the level of the top reinforcement were generated two hours after mixing by pushing the bolts upwards by an amount of 0.04 or 0.08 in. In addition the slabs were deflected as described above.

C.6.2 Revibration Methods

Most specimens were revibrated between 2 and 7 hrs after mixing. Either a surface screed or internal vibrators were employed.

For internal vibration a vibrator tube with a diameter of 2 in. was immerged into the concrete for a period of 20 sec. The revibration energy was varied by varying the distance between insertions of the vibrator. Distances of 12 and 24 in. were selected for "high" and "low" energy levels, respectively. The vibrator had a frequency of approximately 7,000 rpm.

A surface screed used for surface revibration is shown in Fig. C6. An electrically powered vibrator was mounted on a channel 8 in. wide. A metal plate 1/8 in. thick was attached to the bottom of the channel and bent upwards on both ends in order to assure easy gliding of the screed. The vibrator could be mounted on the channel such that the direction of vibration was either parallel or perpendicular to the forward movement of the screed. During revibration the vibrating screed could slide along the sides of the formwork. Rubber cushions between the screed and the formwork kept transmission of vibration energy from the screed directly into the formwork to a minimum. The vibrator mounted on the vibrating screed had an adjustable eccentricity and frequency. The frequency chosen for this investigation was approximately 3,200 cpm. The vibrator could produce a maximum centrifugal force of 900 lb. A value of 720 lb corresponding to 80 percent of the maximum was selected for the high revibration energy level; a value of 20 percent of the maximum corresponding to a centrifugal force of 180 lb was selected for the low energy level. In a few cases an intermediate energy level equivalent to a centrifugal force of 50 percent of the maximum or 440 lb was employed. The speed of forward movement of the screed was approximately 8 sec per ft.

C.6.3 Determination of the Effectiveness of Revibration

Approximately 20 days after casting some concrete slabs were sawed lengthwise with a portable saw into three segments 1 ft wide. The sawed sections were then inspected for cracks with a microscope, and subsequently the cracks were marked and recorded.

C.6.4 Severe Curing Conditions

In Series 5 an attempt was made to simulate severe exposure conditions of the fresh concrete which might lead to surface crusting. Approximately 45 min after casting, the surface of the specimens in Series 5 was heated to a temperature of 95 and 110 F, respectively over a period of 1 1/2 hr or 45 min. At the same time an air current generated by an electric fan was blown across the concrete surface. The heat was generated by 250 watt heating lamps which were spaced 8 by 12 in. apart and which were placed either 12 or 9 in. above the concrete surface. After heating some of the slabs were revibrated as indicated in Table C2e.

C.6.5 Determination of Air Content

The air content of the fresh concrete mix was determined using the pressure test according to ASTM C 457-66T.

The air void parameters of the hardened concrete were obtained using the modified point count apparatus in accordance with ASTM C 457-66T. Cores with a diameter of 4 in. were taken from hardened concrete slabs. The finished surfaces of the cores were lapped only slightly until the surface roughness was eliminated. Thus it was possible to determine the air content near the surface. In order to obtain the air content distribution over the entire thickness of the specimen the cores were then sawed at distances of 1/4, 1/2, 3/4, 1, 3, and 5 in. from the top surface. Each section was prepared by lapping. The air voids were then counted using the modified point count apparatus. This procedure was also used to calculate the cement paste content. Each slice was traversed individually, and eventually all traversed for one specific series were combined into a single calculation of air void parameters.

Because of batch to batch variations in the air content of the fresh concrete, it was difficult to determine conclusively the influence of surface revibration on the air content distribution in the concrete. Therefore, three additional slabs (Series 10) were cast and revibrated at energy levels of 20, 50 or 80 percent. Only half of the surface of the concrete from each batch was subjected to revibration. Cores were then taken from both the revibrated and the non-revibrated sections of the slabs. Thus the effect of revibration on air content distribution could be determined on concrete samples which were cast from the same batch.

C.6.6 Determination of the Effect of Revibration on Concrete Compressive Strength and Concrete Density (Series C)

Three groups of tests were conducted to determine the influence of revibration on compressive strength and density of concrete. In the first group, prisms 6 by 6 by 18 in. were cast horizontally using the same mix as has been described for the main test series. Four hours after mixing several prisms were revibrated on a vibrating table in a horizontal position for a period of 40 sec as described in section D.5.2. During revibration a metal plate producing a vertical static pressure of 0.3 psi was placed on the surface of the prisms. Either retarded or non-retarded concrete was used. The compressive strength of the specimens was then determined after 3, 7, 28 and 90 days respectively.

In an additional series the velocity of a sonic pulse through revibrated and non-revibrated concrete slabs 3 ft by 8 ft by 6 in. was determined. It was assumed that an increase of concrete density due to revibration or due to the closing of cracks may result in a marked increase of the pulse velocity. Both the pulse velocity through the thickness of the slabs and along the slab surface was determined.

The results from the pulse velocity measurements were inclusive, and additional cores with a diameter of 4 in. were taken from both revibrated and non-revibrated slabs. Their density and compressive strength were determined.

C.6.7 Distribution of Revibration Energy Across the Thickness of a Slab (Series ACC)

In order to obtain some information regarding the distance from the top surface at which surface revibration may still be effective, accelerometers were placed vertically in three concrete slabs at various depths from the surface. The accelerometers were covered with an impermeable layer and then were cast in a cube of plaster of Paris with side lengths of approximately 3/4 in. Thus, the overall specific weight of the accelerometers was reduced and was comparable to that of the coarse aggregates used in the concrete mix. The accelerometers were placed approximately 0.75, 2.5, 3.75, and 5.25 in. from the concrete surface. They were tied with string to a small metal frame consisting of indicidual 1/4 in. steel bars. This metal frame in turn was fastened to the reinforcement of the slab. During surface revibration the output of the accelerometers was measured and recorded on an oscilograph and magnetic tape.

C.7 Experimental Results

C.7.1 Development of Cracks in Fresh Concrete - Series P; 3; 4; 5 and 7.

Flexural cracks were generated by deflecting the formwork supporting the fresh concrete 2, 3 or 4 hr after mixing. Figure C7 relates maximum crack width with the deflection and the curvature of the concrete at midspan. Maximum and average crack width are summarized in Table C4. Crack spacing as a function of midspan deflection is presented in Fig. C8. Figure C9 is a photograph showing crack patterns on the concrete surface for "slight", "medium" and "severe" cracking corresponding to a midspan deflection of 0.5, 2, and 3.5 in., respectively. Figure C10 gives crack patterns in sections of concrete which were deflected 2 hr after mixing and sawed in segments 14 days later.

The data indicate that maximum and average crack width and average crack spacing are little affected by variations of the age of concrete at the time of deflection between 2 and 4 hr after mixing. For slabs deflected between 2 and 4 hours after mixing, a curvature in excess of 0.0015 $in.^{-1}$ is required to generate cracks exceeding a depth of 1/2 in. Even at a deflection of 3 1/2 in. only a few cracks penetrated to the level of the top reinforcement. However, tests conducted at a later time indicated that specimens deflected 4 1/2 hours after mixing or approximately two hours before initial set had deeper cracks though the spacing and maximum and average crack width did not significantly deviate from the values observed on specimens which were deflected earlier. This is illustrated in Fig. C11 where cracked sections of specimens deflected 2 or 4 1/2 hr after mixing are compared. The penetration resistance of the concrete when deflected at 4 hr after mixing was still zero while the resistance had increased to 15 psi at 4 1/2 hr after mixing.

During deflection of the slabs the concrete started to separate from the ends of the formwork at a deflection of approximately 1/4 in., corresponding to a curvature of $1.9 \times 10^{-4} in.^{-1}$. The gap between concrete and formwork may be considered a crack, and it was hypothesized that the concentration of deformation at this gap may be responsible for the shallowness of the flexural cracks in the center part of the slab. Therefore, the longitudinal reinforcement of one specimen (ANCH-1) was anchored to the ends of the formwork in order to avoid the separation of the concrete from the formwork. The slab was deflected two hours after mixing, and separation of the concrete from the formwork was indeed avoided. However, spacing, width and depth of the cracks did not significantly deviate from those observed in previous tests.

Two distinctive types of cracks were found in most specimens. The cracks either extended from the concrete surface or cracks formed around the reinforcement without reaching the surface. It is likely that the latter cracks are due to relative movement of the fresh concrete with respect to the reinforcement which may occur during deflection of formwork and concrete.

The flexural cracks were concentrated near reinforcing bars perpendicular to the applied moment particularly for slight and medium cracking. A more even distribution of cracks was observed in severely cracked slabs.

Under the normal laboratory environment of 72 F and 50 percent relative humidity no significant shrinkage cracking or subsidence cracking were observed prior to or after initial set. In the case of severe drying conditions before initial set (wind; 95 and 110 F), which were studied in Series 5, severe shrinkage cracks penetrating beyond the level of the top reinforcement developed as shown in Fig. C23a and C23b.

Subsidence cracking or formation of planes of weakness could not be observed either under regular laboratory conditions or under simulated wind and high temperature conditions. Planes of weakness were, therefore, generated artificially as described in section C.5.5 for a study of the effectiveness of revibration in repairing such cracks. A surface and a cross section of a specimen with artificial and horizontal cracks and flexural cracks is shown in Fig. C.12. The horizontal cracks at the level of the top reinforcement, had a width of approximately 30 x 10^{-3} in. In addition cracks appeared on the concrete surface which were perpendicular to the flexural cracks and which had a width of approximately 10 to 40 x 10^{-3} in.

Non-retarded concrete slabs with an initial set 3 hr 45 min. after mixing were deflected two hr after casting. These specimens showed essentially the same cracking characteristics as retarded concrete (Fig. C19). Variations in percentage of reinforcement had little effect upon flexural cracking (Figs. C22a and C22b).

In conclusion it may be stated that cracking in a bridge deck due to formwork deflection without surface crusting several hours before initial set is insignificant because the cracks are comparatively shallow and because deflections required to develop severe cracking are considerably larger than the deflections which may be expected in the field as long as reasonable construction practices are maintained. However, deflections occurring shortly before initial set may cause severe cracking.

C.7.2 Effectiveness of Revibration in Closing Cracks in Fresh Concrete

C.7.2.1 Method of Revibration; Revibration Energy and Extent of Initial Cracking (Series 1; 7 and 9). A survey of available equipment and consultation with highway departments indicated that at the present time it is not feasible to revibrate bridge deck concrete with external vibrators. The formwork may not be sturdy enough to withstand the stresses due to external vibration. In addition, mounting of vibrators under the formwork will be difficult, time consuming and uneconomical. Furthermore, laboratory tests indicated that external revibration may require the application of a dead weight to the concrete surface during revibration to prevent the formation of additional cracking and a reduction in concrete density. Such precautions are not practical in the field construction of bridge decks. Therefore, the effectiveness of external vibration in closing cracks in the fresh concrete was not studied.

Figure C13 shows the surface of a slab which was severely cracked and internally revibrated four hours after mixing. Half of the slab was hand finished after internal revibration. Cracks on the concrete surface of the unfinished half are marked. Figure C13 indicates that internal revibration closes cracks only in the immediate vicinity of the area at which the vibrator was inserted. Some surface cracks can be closed by subsequent hand finishing as long as the concrete has sufficient workability, but this is a cumbersome and time consuming operation.

Figure C14 shows the distribution of cracks within the cross section of slabs which were severely cracked and internally revibrated 4 hr after mixing. The slabs were not finished after revibration. Internal revibration did not close all surface cracks or cracks around reinforcing bars. Variation in revibration energy i.e. the spacing between vibrator insertions had little influence upon the effectiveness of internal revibration. Because of this limited success internal revibration was not investigated further.

Cross-sections of cracked concrete slabs which were revibrated with a surface screed 4 hr after mixing are shown in Fig. C15. Most surface and internal cracks in the center part of the slab were closed at the low and the high energy level of revibration. The areas up to 6 in. away from the ends of the slabs were not revibrated. The surface appearance of the slabs after revibration was very good, and no additional finishing except brooming or belting would be necessary. Additional finishing immediately after revibration is, however possible, since surface revibration tends to drive some moisture to the surface.

The effectiveness of surface revibration in closing horizontal plane of weakness cracks is illustrated in Fig. C16. Cross sections of slabs from

Series 7 in which flexural cracks and horizontal cracks were generated 2 hrs after mixing are shown. The specimens were revibrated with a surface screed 4 hr after mixing at an intermediate or high energy level. Surface revibration was very effective. With the exception of the end regions, which were not revibrated, all cracks were closed.

With the exception of the tests in Series 9, the vibrator was mounted on the screed with the plane of rotation of the vibrator parallel to flexural cracks and perpendicular to the forward motion of the vibrating screed. In Series 9 the vibrator was mounted with the plane of rotation parallel to the direction of forward motion of the screed. Both methods were equally effective in closing cracks. However, at high energy levels the surface of the concrete was not as smooth and required additional finishing after revibration in the latter case. Vibration perpendicular to the forward motion of the screed, therefore, is preferable.

No specific value for the required minimum revibration energy can be given because of the lack of a suitable method to measure and evaluate vibration of fresh concrete. However, experience gained during this investigation indicates that a revibration energy level which is sufficient to drive a slight moisture film to the entire concrete surface is also sufficient to close most cracks.

C.7.2.2 Time of Revibration (Series 2; 4 and 8)

Since cracking either due to formwork deflection or due to subsidence of the concrete will be severe and harmful only if it occurs several hours after mixing, it is essential that revibration is conducted as late as possible. However, the period of time during which revibration is possible, is limited since the workability of the fresh concrete decreases rapidly as the concrete approaches its initial set. Three test series were conducted to determine the maximum age of concrete at which revibration may be successful.

Figures C17a and C17b show sections of slabs which were deflected at an age of 2 hr and which were revibrated between 3 and 7 hr after mixing at an energy level of 20 percent. In Figures C18a and C18b crack patterns are presented which were observed in slabs revibrated between 3 and 8 1/2 hr after mixing at an energy level of 80 percent. Crack patterns for non-retarded concrete revibrated after 3 hr are given in Fig. C19. Revibration at the lower energy level was reasonably effective in repairing cracks in retarded concrete up to 5 hr after mixing. Most cracks in retarded concrete could be closed up to 7 hr after mixing at the higher energy level. The time during which surface revibration may be effectively conducted depends on the particular concrete and curing conditions. It is, therefore, more instructive to use a parameter which depicts the stiffness of the concrete at the time of revibration. Therefore, the number of external and internal cracks observed in slabs which were surface revibrated at various ages are given in Fig. C20 as a function of the penetration resistance of the concrete according to ASTM 403-68. The region within 12 in. of the ends of the specimens were excluded in determining the number of cracks, since they were not revibrated. Figure C20 includes all data obtained from retarded and non-retarded concrete slabs as well as from specimens which were deflected 4 1/2 hr after mixing. The number of surface cracks in slabs which were not revibrated ranged from 13 to 21 with an average of 17. Between 3 and 7 internal cracks were observed in the non-revibrated specimens. Revibration at an energy level of 20 percent is effective if conducted at a penetration resistance below 30 psi. Revibration at an energy level of 80 percent is effective at a penetration resistance below 60 psi. The relationships of Fig. C20 are valid both for retarded and non-retarded concrete. Thus the influence of retarder, setting time and time of revibration on effectiveness of surface revibration can be expressed by one parameter, the penetration resistance.

Figure C21 shows crack patterns which were obtained from specimens deflected 4 1/2 hr after mixing. As noted in Section C.6.2.1, late deflection resulted in cracks deeper than those observed in slabs which were deflected between 2 and 4 hr after mixing. Figure C21 indicates that most cracks could be closed by surface revibration 5 hr after mixing at an energy level of 80 percent; the number of cracks observed after revibration can be expressed by the same relationship given in Fig. C20 for the slabs deflected 2 hr after mixing.

The criterion for the required minimum revibration energy given in the previous section was confirmed by the tests conducted in Series 2, 4 and 8. Revibration is effective as long as a thin moisture film appears on the entire concrete surface. If the concrete is too stiff to be revibrated effectively the surface screed tends to ride on the high spots of the concrete surface, and the areas between the high spots remain virtually unrevibrated.

C.7.2.3 Effect of Reinforcement Detailing (Series 3)

A study of reinforcement detailing was included in an attempt to form planes of weakness and subsidence cracks. As mentioned earlier variations in reinforcement did not have this effect. Figures C22a and C22b show crack patterns in concrete slabs with a percentage of the top reinforcement perpendicular to the cracks of 0.57 and 1.28, respectively. The slabs were cracked severely 2 hr after mixing and were revibrated 4 hr after mixing. The observed crack patterns are not significantly influenced by the reinforcement. Revibration at the 80 percent energy level repaired most of the cracks.

C.7.2.4 Effect of Curing Conditions (Series 5)

In the first subseries concrete slabs were exposed to hot, dry air generating a temperature of 110 F at the concrete surface for a period of 45 min. This treatment resulted in severe crusting of the surface and the formation of deep shrinkage cracks as shown in the top portion of Fig. C23a. The specimens were revibrated with the surface screed at the 80 percent energy level immediately after heating. The crack patterns observed in a specimen after revibration are shown in the lower portion of Fig. C23a. Though most of the deep cracks could be closed by revibration the surface crust was not broken, and a large number of shallow surface cracks was generated by revibration. The concrete surface was rough, and finishing after revibration was difficult.

Figure C23b shows the crack patterns in slabs which were heated for 90 min to a temperature of 95 F at the concrete surface. The exposure to hot and dry air resulted in crusting and shrinkage cracks as indicated in the top half of Fig. C23b. Most of the cracks were repaired by surface revibration. The surface crust was partially broken. However, finishing after revibration was still necessary to obtain a smooth surface.

In these tests it became apparent that surface revibration can improve moderately crusted concrete surfaces. However, it cannot completely eliminate the effects of severe exposure of fresh concrete to warm and dry air since the extensive finishing required after revibration will cause considerable problems in actual bridge deck construction.

C.7.3 Effect of Revibration on Concrete Strength (Series C)

Figure C24 shows the influence of revibration on the compressive strength of prisms 6 by 6 by 18 in. Four specimens were tested for each combination of variables. Revibration had no statistically significant effect on the compressive strength of retarded concrete. The compressive strength of the non-retarded concrete was slightly increased by revibration.

These data agree with the findings of previous investigations which were described in Section 2.2. According to these studies revibration several hours before initial set has little influence on the compressive strength of concrete. Revibration shortly before or after initial set may, however, lead to a noticeable increase of concrete compressive strength. At the time of revibration the retarded concrete was 3 hr away from its initial set. Consequently, revibration had little effect on compressive strength. The non-retarded concrete was revibrated one hour before its initial set resulting in the strength increase observed by other investigators.

Pulse velocity measurements through the thickness of revibrated and non-revibrated slabs were used to evaluate the effect of surface revibration on strength and density of retarded concrete. The results of these studies are summarized in Table C5. According to these data surface revibration at an energy level of 20 percent resulted in a slight reduction of unit weight, compressive strength and relative dynamic modulus compared to the corresponding values for the non-revibrated slabs. The observed differences for these three values are consistant with each other but are not statistically significant. Surface revibration at the 80 percent energy level led to an increase of unit weight, strength and relative dynamic modulus. From these data as well as from the results of previous studies it is concluded that revibration has very little damaging effect on concrete compressive strength and density. At higher energy levels it may lead to a slight improvement of these concrete properties.

C.7.4 Effect of Revibration on Air Void Characteristic of Concrete (Series 10 and Phase 3b)

The distributions of air content, paste content and spacing factor in revibrated and non-revibrated concrete are shown in Figs. C25a, C25b and C25c. The data are summarized in Table C6. According to Figs. C25 the hand finishing procedures resulted in a reduction of the air content and in an increase of the paste content close to the concrete surface even in concrete which was not revibrated. Surface revibration increased this effect.

The following summarizes the spacing factors of the surface layers of surface revibrated and non-revibrated sections of three slabs:

Energy Level	Spacing Factor at Surface No Revibration	Spacing Factor at Surface Revibration
20%	0.0068 in.	0.0074 in.
50%	0.0067 in.	0.0078 in.
80%	0.0073 in.	0.0079 in.

Revibration caused an increase of the spacing factor, that was small and should not be of major significance for concrete durability as long as the initial air content of the concrete is sufficient. Revibration did not affect the air void system of concrete at a distance of more than 1 in. from the concrete surface.

The influence of external revibration on the air void characteristics was investigated within Phase 3a of the durability studies. The data are summarized in Table C7a and C7b. No pronounced effect of external revibration on the air void characteristics and the paste content of the concrete could be observed since the differences between the properties of revibrated and non-revibrated concrete are within the accuracy of the experimental procedures and the variations to be expected in concrete.

C.7.5 Distribution of Revibration Energy (Series P and Series 1, Phase 3a)

Three specimens 3 ft by 8 ft by 6 in. of the pilot Series P, Phase 2 were used to measure the distribution of vibration energy in surface revibrated concrete. Six companion specimens 22 by 22 by 6 in. of Series 1, Phase 3a contained accelerometers to determine the distribution of vibration energy during external revibration. The specimens were revibrated 4 hrs after mixing at different energy levels.

The vertical acceleration of aggregate particles in concrete during external revibration of small slabs on a vibrating table described in Section D5.2 is shown in Fig. C26 as a fraction of the acceleration of gravity, g, for specimens with and without a dead weight on the concrete surface. Since the vibration energy is introduced into the specimen through the bottom of the formwork, the acceleration decreases with increasing distance from the bottom. However, placement of a steel plate on the concrete surface markedly reduced this tendency and resulted in a more uniform distribution of the revibration energy.

The results of accelerometer measurements at the center of the large slabs which were surface revibrated at an 80 percent energy level are shown in Figs. C27 and C28. The data obtained at a 20 percent energy level are presented in Figs. C29 and C30. Generally the acceleration decreases with increasing distance from the concrete surface (see Figs. C27 and C29). However, particularly at the high energy level revibration is transmitted from the surface screed through the sides of the formwork which supports the screed into the bottom plate of the formwork. Consequently, the concrete at the bottom of the specimen is accelerated more than the regions at midheight of the specimen. It is likely that the amount of revibration energy which may be transmitted through the sides of the formwork decreases as the width of the slab is increased and, therefore, may be negligible in actual bridge decks. Figures C28 and C30 show that the acceleration at the center of the slabs decreases as the distance of the vibrating screed from the center increases. However, surface revibration is still noticeable even if the screed is 3 ft away from the center.

A comparison of the accelerometer measurements at the 20 percent and 80 percent energy level indicates that the acceleration of aggregate particles in fresh concrete varies approximately linearly with the centrifugal force of the vibrator. The accelerometer measurements were useful in selecting the revibration parameters for this investigation and gaining an insight into the distribution of revibration energy in the concrete. However, the required experimental set-up and the precautions necessary to obtain reliable data prohibit extensive use of accelerometer tests as a measure of the required revibration energy for concrete in the field.

Appendix D

Durability Studies - Phase 3

D.1 Objective and Scope

The durability studies were divided into two subphases. The objective of Phase 3a was to conduct a general survey of the effect of revibration on freeze-thaw durability and abrasion resistance of concrete. For Phase 3b the results obtained from Phase 2 and Phase 3a were then used to select the parameters to be studied on large slabs as models of actual reinforced concrete bridge decks.

Phase 3a is subdivided into five subseries. Within each series the age of concrete at the time of revibration as well as the revibration energy level were varied. However, different concrete properties were investigated for each subseries. The following subseries were studied:

Series 1A: Retarded concrete, air content between 5.5 and 7 percent reinforced specimens.

Series 2A: Retarded concrete, air content between 4 and 5 percent, reinforced specimens.

Series 2B: Non-retarded concrete; air content between 4 and 5 per cent, reinforced specimens.

Series 2C: Non-retarded concrete, air content between 5.5 and 7 per cent, reinforced specimens.

Series 3: Retarded concrete, air content between 5.5 and 7 per cent, specimens without reinforcement.

Phase 3b consisted of five subseries:

Series 1D: Revibration energy and extent of initial cracking.

Series 2D: Time of initial set.

Series 3D: Effect of plane of weakness cracks.

Series 4D: Effect of air content.

Series 5D: Finishing procedures.

One-hundred specimens were tested in Phase 3a. In Phase 3b, 22 specimens were investigated.

The test data showed a pronounced difference in the freeze-thaw resistance of retarded and non-retarded concrete. In order to further investigate this observation plain concrete prisms 3 by 3 by 15 in. were subjected to freezing and thawing while exposed to deicing salts. Both retarded as well as non-retarded and revibrated and non-revibrated concretes were studied.

D.2 Description of Specimens

In Phase 3a plain and reinforced specimens 22 by 22 by 6 in. were used. The layout of the reinforcement is shown in Fig. D31.

The specimens were designated by a sequence of terms describing the test series, the age at revibration, T, and the revibration energy level, e. The following values were chosen for T and e:

T_1 = revibration 2 hr after mixing

T_2 = revibration 4 hr after mixing

T_3 = revibration 5 hr after mixing

e_1 = duration of revibration 10 sec.

e_2 = duration of revibration 25 sec.

e_3 = duration of revibration 40 sec.

Control specimens used to determine air void distribution and abrasion resistance are designated "C". The particular properties of each specimen tested in Phase 3a are summarized in Table D8.

In Phase 3b reinforced concrete slabs 8 ft by 3 ft by 6 in. were tested. The reinforcement pattern was similar to the layout for the Phase 2 specimens as described in section C2 and shown in Fig. C3a. A description of all specimens is given in Tables D9a and D9b.

D.3 Materials and Mix Proportions

The same materials and mix proportions which were used for the Phase 2 specimens also were used for the specimens within Phase 3. They are described in sections C.3 and C.4.

D.4 Fabrication of Specimens

Phase 3a: The test slabs 22 by 22 by 6 in. were cast in rigid steel forms. The layout of the reinforcement is shown in Fig. D31. A concrete cover of 1 1/2 in. was maintained throughout this phase. The mixing and casting procedures employed were as follows:

An 8 cu ft batch was mixed in a batch plant with a horizontal tub mixer. The dry ingredients were mixed for 1 minute before adding some water containing the air entraining agent and additional water containing the retarder. The wet mixture was then mixed for three additional minutes. The concrete was placed in each form and initially vibrated on a vibrating table for approximately 15 sec. Since the volume required for each subseries was larger than the capacity of the mixer several batches had to be cast for each series as indicated in Table D8.

Control slabs to determine abrasion resistance and air content distribution as well as compression test cylinders to determine the 28-day strength of the concrete were cast with most batches.

All specimens were struck off and finished with an aluminum trowel immediately after casting. They were covered with wet burlap approximately seven hours after mixing. The specimens were then moist-cured for an additional six days. The moist curing period was followed by 14 days of air drying at a relative humidity of 50 percent and a temperature of 70 F. During this drying period rubber strips were attached to the surface of the specimens to form dikes. The specimens were ponded with tap water approximately two days before exposure to freezing and thawing at an age of 21 days.

Phase 3b: For most of the specimens tested in Phase 3b the casting procedures already described for the Phase 2 specimens in section C.5 were used. All specimens were moist cured up to an age of 7 days. They were then dried for an additional 14 days at a relative humidity of 50 percent and a temperature of 70 F. Prior to freezing and thawing rubber strips were glued on the concrete surface and the specimens were ponded with tap water two days before exposure to freezing and thawing at an age of 21 days.

D.5 Test Procedures

D.5.1 Finishing

All specimens tested in Phase 3a were finished with an aluminum trowel immediately after casting. No additional finishing after revibration was employed. The same procedure was used for the specimens of Phase 3b except for the slabs of subseries 5D. If properly conducted, revibration with a surface screed resulted in a smooth finish. Since each additional finishing step tends to reduce the air content of the surface mortar the initial hand finishing was omitted for some specimens of subseries 5D and finishing was obtained only by surface revibration. In the same series some specimens were tested which were not finished prior to revibration but were finished with an aluminum trowel after revibration.

D.5.2 Revibration Methods

The specimens tested within Phase 3a were revibrated externally on a vibrating table. For this, the same vibrator which was used for the surface screed was attached to the vibrating table. An eccentricity of 80 percent corresponding to a centrifugal force of 720 lb and a frequency of 3200 cpm were kept constant. Revibration energy was varied by changing the duration of vibration between 10 and 40 sec. During revibration the formwork containing the concrete was rigidly attached to the vibrating table. A steel plate generating a vertical static pressure of 0.3 psi was placed on the concrete surface during the revibration process. This method proved to be necessary in order to avoid the development of surface cracks during the revibration process. This method proved to be necessary in order to avoid the development of surface cracks during revibration which may have been caused by the relative movement of the concrete with respect to the reinforcing bars. In addition the steel plate ensured revibration of the surface layers of the concrete and resulted in a more uniform distribution of revibration energy as shown in section C.6.2.7.

For the specimens of Phase 3b a surface screed as described in section C.6.2 was used for revibration.

D.5.3 Freeze-Thaw Testing

During freeze-thaw testing of all specimens within Phase 3a and Phase 3b the specimens remained ponded with a 4 percent sodium chloride solution which was replaced only at the time of the rating of scaling. The solution was contained by rubber chamfer stripping cut to size and attached to the specimens by means of plastic rubber cement. Since the specimens within Phase 3b were deflected prior to hardening, their surface was curved. Therefore the surface was subdivided into three sections, and each section was ponded separately as shown in Fig. D32. All specimens were subjected to cycles of freezing and thawing in an environmental testing unit as described in Ref. 5. This unit was designed to allow the removal of two 4 x 12 ft roof sections using an overhead crane and thereby permitted direct placement by crane of the slabs into their respective locations. Up to 30 small slabs from Phase 3a and up to 6 large slabs from Phase 3b could be tested simultaneously. During freezing and thawing the small slabs were supported along two lines approximately 15 in. apart. The large slabs were supported approximately 5 in. from their ends. The environmental testing unit was programmed such that the specimens were subjected to one freezing and thawing cycle per day with internal concrete temperatures ranging from 0 F to 40 F. The temperature was monitored by thermocouples embedded in the center of a control specimen.

After every seven cycles each specimen was removed from the testing unit, hosed off and then rated according to the following numerical scale:

0 = no scale

1 = scattered spots of very light scale

2 = scattered spots of light scale

3 = light scale over about half the surface

4 = light scale over most of the surface

5 = light scale over most of the surface, a few moderately deep spots

6 = scattered spots of moderately deep scale

7 = moderately deep scale over half the surface

8 = moderately deep scale over the entire surface

9 = scattered spots of deep scale, remainder moderately scale

10 = deep scale over the entire surface

A similar rating scale has been used in two previous investigations conducted at the University of Illinois (5, 6). A scaling was considered to be very light when it consisted of loss of a paper thin film of mortar from the finished surface. Light scaling occurred when particles of mortar generally 1/8 to 1/4 in. in thickness were lost. Scaling was described as moderate when additional mortar was removed together with smaller aggregate particles. Surface deterioration resulting from "pop out" was also considered to be scaling. Deep scaling was said to have occurred when larger aggregate particles could easily be removed from the scaled surface at the time of rating.

Photographs of the specimens were taken in addition to the rating. For the small slabs of Phase 3a one photograph was taken per specimen. For the specimens within Phase 3b each specimen was subdivided into eight sub-areas, and photographs were taken for each area.

Immediately following the rating, the specimens were again ponded with a 4 percent sodium chloride solution and then freezing and thawing cycles were resumed. In most cases, the periodic rating of specimens continued until the ratings became high enough to denote failure of the surface. In a number of instances testing had to be interrupted for comparatively short periods in order to repair leaking dikes.

The small prisms 3 by 3 by 15 in. were tested in an automatic freezing and thawing cabinet. The test procedure used for these tests was similar to the procedure described in ASTM C 290 except that all specimens were frozen and thawed in a 4 percent sodium chloride solution. Earlier tests had shown that freeze-thaw deterioration was mainly concentrated on the surface of the specimen. Therefore, the specimens showed an appreciable weight loss but a less pronounced change in the dynamic modulus. Therefore, weight loss during freezing and thawing was used as the only measure of concrete deterioration. The concrete prisms were hosed off, surface dried, and weighed approximately every 20 cycles. The tests were discontinued after 140 cycles at which time the specimens were photographed.

D.5.4 Determination of Air Content

The same procedures described for the tests within Phase 2 were employed for the studies within Phases 3a and 3b.

D.5.5 Determination of Abrasion Resistance

The abrasion resistance of revibrated and non-revibrated concrete was determined in accordance with the test method described in ASTM C 418-68. Cores with a diameter of 4 in. were taken from the large slabs 8 ft by 3 ft by 6 in. The cores were then brought to a saturated surface dry state and then the specimens were tested in a sand blast cabinet. After each test the specimens were washed and weighed to determine the amount of material abraided. A total of five tests was conducted on each core.

D.6 Experimental Results

D.6.1 Influence of Revibration on the Durability Characteristics of Uncracked Concrete - Phase 3a

The main variables to be studied in Subseries 1A and 2A were the age of concrete at the time of external revibration, T, the duration of revibration, e, and the air content. In Fig. D33 the surface deterioration ratings of retarded concrete with an air content varying from 5.5 to 6.5 percent are given as a function of the number of cycles of freezing and thawing. Each curve represents the average of two to four similar specimens. The results of the individual tests are given in Appendix F.

Figure D33 indicates that external revibration conducted 2 hr after mixing may slightly improve the frost resistance of concrete. A similar trend is found in Fig. D34 which shows the surface deterioration ratings of retarded concrete with an air content ranging from 4.5 to 4.9 percent. However, due to the considerable scatter of the individual data the difference between revibrated and non-revibrated concrete is statistically insignificant and is overshadowed by batch to batch variations in the air content of the concrete. The same is true for the effect of duration of revibration and age of concrete at the time of revibration on concrete durability. The influence of the air content on the surface deterioration of concrete after 21 cycles is presented in Figs. D35a and D35b. Surface deterioration decreased as the air content increased, however, no clear distinction between revibrated and non-revibrated concrete can be made.

Figure D36 shows the results of the freezing and thawing tests on non-retarded concrete (Subseries 2B and 2C) with air contents of 4.5 and 6.5 percent, respectively. No statistically significant difference between revibrated and not revibrated concrete was found. However, the non-retarded concrete was considerably more durable than retarded concrete. The characteristics of the air void systems of retarded and non-retarded as well as revibrated and not revibrated concrete were summarized in Tables C7a and C7b. External revibration had no marked effect on air content, spacing factor and paste content of the surface layers of the concrete. However, the spacing factor of the retarded concrete was in all observed cases slightly larger than that of the non-retarded concrete which may at least in part be responsible for the differences in the surface durability of the two concretes. Differences in the time of finishing or revibration relative to the time of initial set between retarded and non-retarded concrete are with all likelihood not responsible for the differences in durability since variations in the time of revibration for a given concrete had no significant influence on surface deterioration of the retarded concrete or of the non-retarded concrete. It should also be noted that both the air-entraining agent and the retarder were considered compatible and were added separately to the fresh concrete mix.

In Series 3 of Phase 3b unreinforced retarded concrete specimens were subjected to freezing and thawing. This test series was included in the investigation since it was expected that cracks would be less likely to develop due to early shrinkage in unreinforced specimens than in reinforced specimens. Consequently revibration should have less influence on the surface deterioration of plain concrete than it might have on reinforced specimens. Figure D37 shows that the unreinforced specimens were more durable than the reinforced specimens. However, no convincing explanation for this unexpected difference can be given.

Typical examples of the type of surface deterioration observed in Phase 3b are shown in Fig. D38. The deterioration consisted in all cases of spotty scaling and was independent of the location of the reinforcement.

D.6.2 Influence of Revibration on the Durability of Cracked Concrete Slabs - Phase 3b

D.6.2.1 Effect of Extent of Cracking and Revibration Energy (Series 1D and 3D)

Figure D39 shows the average surface deterioration ratings of concrete slabs which were cracked to various degrees two hours after mixing. The individual data obtained in the tests within Phase 3b are given in Appendix F. There is no clear indication that surface cracking or horizontal plane of weakness cracking resulted in reduced durability of the concrete surface when exposed to accelerated freezing and thawing in the laboratory. In uncracked slabs uniformly distributed scaling was observed. Scaling of the cracked slabs was slightly more pronounced in the vicinity of the cracks for approximately 14 freeze-thaw cycles; then scaling was essentially uniform. No surface spalling was observed.

The surface durability of surface revibrated, cracked slabs and cracked slabs without revibration is presented in Fig. D40. The relationship between deterioration rating and number of freeze-thaw cycles for concrete without revibration given in Fig. D40 corresponds to the average of all data from Fig. D39. Figure D39 indicates that revibrated slabs performed better than unrevibrated specimens. A statistical evaluation of all data showed, however, that the difference between the average of all revibrated and all not revibrated slabs is not statistically significant. It can be stated that revibration does not impair concrete durability despite the fact that the spacing factor of the surface layer may be slightly increased by revibration as was shown in section C.7.4. It is likely that the increase in spacing factor is offset by the improved compaction and strength of the concrete surface layers. A similar observation has been reported in Reference 6.

The only type of deterioration observed in these tests was scaling. Typical photographs of the appearance of the concrete surface after various cycles of freezing and thawing are shown in Figs. D41a and D42b. The cracked slabs showed more deterioration in the vicinity of the cracks while the revibrated slabs deteriorated uniformly over the surface.

D.6.2.2 Effect of Retarder (Series 2D). Figure D42 indicates that the durability of non-retarded concrete was considerably better than that of retarded concrete. This is in agreement with the test results obtained in Phase 3a. A comparison of the specimens made with non-retarded concrete shows that severe surface cracking reduced concrete durability. Subsequent revibration resulted in a slight increase of the frost resistance of the non-retarded concrete.

In order to further verify the effect of the particular retarder used in this study on concrete frost resistance, prisms 3 by 3 by 15 in. were exposed to 112 cycles of freezing and thawing in an automatic freezing and thawing cabinet. The results of this test series are shown in Fig. D43 where the average weight loss as determined on 6 specimens for each variable is given as a function of the number of cycles of freezing and thawing. Again, the non-retarded concrete was significantly more frost resistant than the retarded concrete.

D.6.2.3 Effect of Air Content (Series 4D). The retarded concrete had a higher compressive strength than the non-retarded concrete if the volume of entrained air was approximately equal in both concretes. Therefore, in tests conducted within subseries 4D the air content of the retarded concrete was raised to such a level that the compressive strength of the retarded concrete approached that of the non-retarded concrete. The increased air content resulted in a marked increase of the surface durability of the retarded concrete as shown in Fig. D44. The following table gives average compressive strength, air content and surface deterioration of retarded and non-retarded concrete after 40 cycles of freezing and thawing.

Retarder	Air Content %	Compressive Strength $f'_{c\ 28}$ (psi)	Surface Deterioration Rating After 40 Freezing and Thawing Cycles
yes	6.2	5460	6.4
yes	8.1	4860	2.3
no	6.2	4400	3.1

Apparently it is possible with the particular retarder used in this investigation to produce retarded concrete with a strength and surface durability which is at least equal to that of non-retarded concrete.

D.6.2.4 <u>Effect of Finishing Procedures</u> (Series 5D). Surface revibration resulted in an acceptable finish of the concrete surface. Since every manipulation of the fresh concrete surface tends to alter the air content of the surface layer it was hoped that elimination of hand finishing prior to revibration may offset the possible loss of air due to surface revibration and may result in an improved surface durability. However, the data shown in Fig. D45 indicate, that elimination of hand finishing immediately after casting had little influence on the durability of revibrated or non-revibrated specimens.

Figure D45 also shows the influence of hand finishing 4 1/2 hr after mixing. The durability of a specimen which was revibrated immediately before hand finishing was comparable to the durability of specimens which were finished immediately after casting. Late finishing without revibration, however, increased the surface deterioration of the concrete. Since the concrete of this particular specimen was still two hours away from its initial set, the late finishing may have interrupted the bleeding process and thus reduced surface durability. Improved compaction due to revibration may offset this effect.

D.6.2.5 Effect of Surface Revibration on Abrasion Resistance of Concrete (Phase 2, Series 10). Cores were taken from specimens of Series 10, Phase 2 in order to compare the abrasion resistance of concrete with and without surface revibration. The data obtained are summarized in Table D10 and show that surface revibration had no pronounced effect on abrasion resistance. Batch to batch variations in the air content were considerably more significant.

Appendix E
Field Applications-Phase 4

In order to investigate the feasibility of revibration of bridge deck concrete in the field and to observe their long time performance portions of three bridge decks under construction in Illinois and Kansas were revibrated.

On the basis of the laboratory experiments the following guidelines for the field experiments were selected:

(a) the bridge deck concrete shall be revibrated with a vibrating screed

(b) revibration shall be conducted after the penetration resistance of the concrete reaches a value of approximately 25 psi

(c) the bridge deck concrete shall be finished prior to revibration, and additional finishing after revibration shall be kept to a minimum

(d) no particular requirements regarding concrete mix proportions in addition to those developed by the respective highway departments will be made. The use of set retarding admixtures is desirable but not mandatory.

E.1 Bridge Deck in Illinois

Field work was conducted on the reinforced concrete deck of a skewed, continuous span, noncomposite bridge with structural steel I beams. The bridge is located on Illinois highway 110 approximately 12 miles west of Champaign, Illinois, and crosses the Interstate Highway 172. The spans of the bridge are 51 ft-1 1/4 in.; 81 ft-1 1/4 in.; 81 ft-1 1/4 in. and 51 ft-1 1/4 in. respectively. A schematic view and a cross-section of the bridge are shown in Fig. E 46.

On July 10, 1969, a section of the bridge deck 3 ft-3 in. wide and 15 ft extending in both directions from the center support of the bridge was cast and revibrated. This section is adjacent to the safety curbs along the south edge of the bridge as shown in Fig. E46 and is separated from the main lanes of the deck by a longitudinal construction joint. The main deck had been cast a week prior to the experiment, and the safety curbs were cast a few days after casting of the revibrated segment. The mix proportion of the concrete are given in Table E11. The results of a standard penetration resistance test of the bridge deck concrete are shown in Fig. E47. The air temperature during the casting period ranged from 84 to 89 F, the relative humidity was approximately 65 percent, and the day was sunny with only slight westerly winds.

The same vibrating screed which was used in the laboratory experiments and which is shown in Fig. C6 was used to revibrate the bridge deck concrete. A revibration energy level of 20 percent as defined in Section C6.2 of this report and a direction of revibration perpendicular to the forward movement of the screed were selected. During revibration one edge of the vibrating screed rested on the hardened concrete of the main deck. The other edge of the screed was supported by a 2 by 4 in. lumber. The concrete was struck off and hand finished with aluminum floats immediately after it had been placed and compacted by internal vibration. The concrete surface was revibrated approximately 2 hrs after placing. At that time the penetration resistance of a concrete sample taken from the same batch as the bridge deck concrete was approximately 25 psi. This sample was covered with moist burlap following casting, while the bridge deck was partially exposed to sunshine so that the concrete in the bridge deck set faster than the control specimen. Therefore at the low revibration energy level used for this experiment only about 80 percent of the revibrated concrete surface showed a thin moisture film after revibration. In addition, revibration caused the concrete to settle slightly below the level of the hardened concrete of the adjacent main lanes of the bridge deck. In order to achieve a smooth and continuous transition across the longitudinal construction joint hand finishing after revibration was required. At that time the concrete approached its initial set and was very difficult to finish.

The experiment was a partial success since it showed that bridge deck concrete indeed can be revibrated if suitable equipment is available and if the time of revibration is properly selected. The study was helpful in planning the subsequent tests to be conducted in Kansas and demonstrated clearly that finishing after revibration should be eliminated as far as possible.

The bridge deck was moist cured for seven days after casting and was inspected several times since then. No apparent differences between the revibrated and the non-revibrated sections of the deck could be found. There was no indication of cracking except a fine transverse hairline crack through the revibrated section directly above the center support of the bridge as shown in Fig. E48. This crack started at an expansion joint in the safety curb and continued across the revibrated section and thelongitudinal construction joint a few inches into the main deck. It is very unlikely that this crack can be attributed to revibration of the bridge deck concrete. It rather may be due to the dead weight of the superstructure and may have formed after stripping the form work.

Observations of the bridge deck will be continued.

E.2 Bridge Decks in Kansas

The studies were conducted on two identical bridges, Br. No. 35W-40-2.00 and Br. No. 35W-40-5.00, which cross the Interstate Highway I35W near Newton, Kansas. The non-composite bridges were continuous with spans of 43 ft-92 ft-92 ft-43 ft and consisted of welded steel plate girders with a reinforced concrete deck. Elevation and cross-section of the bridges are shown in Fig. E49. Placement of the deck concrete was started at the west end and was discontinued just short of the second pier for each bridge; then casting was continued starting from the east end of the bridges up to a header. This casting sequence was used to prevent uplift of the short spans of the bridges at the abutments.

The mix proportions and properties of the bridge deck concrete are summarized in Table E11. Figure E47 shows the penetration resistance of the concrete. The test specimens used to determine initial set were either covered with wet burlap during setting or were left uncovered and placed next to the bridge deck in order to expose them to the same environment as the bridge deck. The concrete for the deck of bridge 35W-40-2.00 contained no retarder; for bridge 35W-40-5.00 retarded concrete was used.

On August 27, 1969, the bridge deck 35W-40-2.00 was cast. During the earlier part of the day the sky was overcast with temperatures ranging from 72 F to 78 F. There were only light winds and a relative humidity around 60 percent. The entire width of the deck extending from the east abutment over a length of 82 ft was revibrated. The vibrating screed which was used for this experiment is shown in Fig. E50. The screed was designed and constructed by the local contractor. It consisted of a steel pan, 12 in. wide and 1/4 in. thick which was stiffened by a steel T-beam of variable depth. A vibrator with variable eccentricity and frequency was driven by a gasoline 3 HP motor and was mounted at the center of the screed such that the direction of revibration was parralel to the forward movement of the screed. During the experiment the frequency of the vibrator was approximately 3200 cpm. An intermediate setting of the eccentricity of the vibrator was chosen but no data on the magnitude of the centrifugal force of the vibrator were available. In order to move the screed, steel cables were firmly attached to the formwork approximately 30 ft in front of the screed. These cables ran through hooks welded to the screed stiffners to rotating drums in the center of the screed. The drums were driven by the same motor used to operate the vibrator as shown in Fig. E50. Rotation of these motor driven drums resulted in a forward movement of the screed.

After placing and internal vibration the concrete was struck off with a finishing machine. Then a thin spray of a water emulsion of aliphatic alcohol was applied to the concrete surface.* It was hoped that this spray would result in the formation of a monomolecular layer on the concrete surface which retards the evaporation of bleeding water and prevents crusting.(24) Revibration of the bridge deck was started approximately 1 1/2 hr after casting. At this time the entire concrete of the deck within the 43 ft span of the bridge had been placed. At the beginning of revibration a covered control specimen showed a penetration resistance of approximately 25 psi. During revibration the screed was free-floating on the concrete surface and travelled at a speed of about 1 ft per min.

The revibration energy was sufficient to drive additional moisture to the concrete surface. However, the screed did not precisely match the profile of the bridge deck surface, and areas near the longitudinal axis of the bridge deck remained unrevibrated as shown in Fig. E51. In addition, the free-floating screed tended to sink into the concrete. By slightly adjusting the location of the pulling cables and by lifting the screed on the handles attached to both ends, sinking of the screed could be reduced but not avoided. Finally, each time the vibrator was stopped a noticeable mark was left on the concrete surface. Extensive and cumbersome hand finishing after revibration was required because of these shortcomings. The experiment showed, however, that continuous revibration of the entire width of the bridge deck is possible if the screed is supported during revibration and if its shape can

*The use of the spray was suggested by W. M. Stingley, State Highway Commission of Kansas.

be adjusted to match closely the profile of the bridge.

A new vibrating screed was designed and constructed by the contractor on the basis of the experience gained during revibration of the bridge deck 35A-40-2.00. A pan 15 3/4 in. wide was attached to the strike off screeds of a finishing machine as shown in Figs. E 52a and E52b. The distance of the strike off screeds to the supporting structure of the finishing machine could be adjusted at five points spaced approximately 60 in. apart. By adjusting the strike off screeds it was possible to adapt the vibrating pan to the desired profile of the bridge deck. Two surface vibrators driven by 1 HP electric motors and rotating in a plane perpendicular to the forward movement of the screed were fixed to the pan approximately at its third points as shown in Fig. E52. No information about the centrifugal force of the vibrators was available. The vibration frequency was uniform over the length of the pan and was approximately 3500 cpm. However, on the basis of visual ovservation it is likely that the vibration amplitude was not uniform and probably was lower at the extreme ends of the pan. The finishing machine to which the vibrating pan had been attached had four wheels on each side and was running on water pipes which were firmly fixed to the form work of the bridge deck.

On September 23, 1969, the vibrating equipment described above was used to revibrate the deck of bridge No. 35W-40-5.00. The entire width of the deck starting from the east end and extending over a length of 133 ft was revibrated. Sunny skies with temperature ranging from 70 F to 85 F, a relative humidity around 60 percent and moderate winds prevailed during most of the day. The concrete was internally vibrated after placing and struck off with a finishing machine. Following these procedures parts of the concrete surface were sprayed with the water emulsion of aliphatic alcohols described previously.

Prior to revibration the second finishing machine with the attached vibrating pan was placed into position and adjusted to the profile of the bridge deck. Approximately 2 1/2 hr after casting started revibration of the bridge deck was commenced. At that time placement of the concrete had progressed up to the center of the second span. At the beginning of revibration the uncovered control sample had a penetration resistance of 28 psi while the covered sample showed a value of 18 psi. The speed of forward movement of the vibrator was varied between 4 and 8 in. per min. After minor readjustments the vibrating pan followed the profile of the bridge deck very closely, and the entire width of the deck appeared to be sufficiently revibrated. Very little additional finishing except belting and brooming was required after surface revibration in those areas which were sprayed with the water - alcohol-emulsion immediately after the initial finishing procedures. The appearance of the concrete surface after revibration is shown in Fig. D53. A narrow segment of the bridge deck next to the east abutment and approximately 20 ft long was not sprayed after placing, and light crusting of the concrete surface may have occurred. In this case the revibration energy near the ends of the screed was insufficient to brake the crust, and cracks in the concrete surface were formed as shown in Fig. D54. Similar cracks were found in the laboratory studies, Series 5, Phase 2 where the effectiveness of revibration following extreme curing conditions was studied. In those cases additional hand finishing was required. However, the laboratory experiments showed that increased revibration energy may break up the crust and may result in a satisfactory concrete surface.

After revibration was completed it become apparent that the surface of the bridge deck was not true but had a slightly wavy appearance. This was probably due to the fact that the water pipes supporting the finishing machine with the attached vibrating pan were coupled by sleaves at close intervals.

Each time a wheel of the finishing machine had to pass over such a sleave the entire machine was slightly lifted resulting in the uneven surface of the concrete. In addition it is possible that interference between the two independent vibrators mounted on the vibrating pan may have caused variations in the vibration amplitude.

The second experiment in Kansas clearly showed that revibration of bridge deck concrete is feasible and if properly timed can be conducted without additional finishing. The equipment used in the second experiment was efficient though it has some obvious disadvantages which may be corrected in the future. Stiff springs placed between the finishing machine and the supporting wheels would eliminate the effect of a local unevenness of the supporting pipes or rails. Vibrators with a larger and adjustable centrifugal force are required. One vibrator placed at the center of the vibrating pan may eliminate possible interference between several individual vibrators. The use of a spray to slow down surface moisture evaporation and to prevent surface crusting particularly when retarded concrete is used appears to be very promising. Further studies and development of equipment may show that the use of several smaller vibrating screeds or one small screed which can travel laterally along a supporting structure may have definite advantages in comparison to the continuous, large screed used in these experiments since it would be easier to locally adjust the revibration energy or duration of revibration. Such adjustments may be necessary because of batch to batch variations or because of localized variations of the exposure conditions of the concrete within a bridge deck.

Inspection of the bridge decks conducted by the staff of the Highway Commission of Kansas soon after construction showed no apparent differences between revibrated and non-revibrated concrete. Cores have been taken from the decks. Visual inspection of the cores indicate that the concrete close to the revibrated surface was compacted more than the non-revibrated concrete. Microscopic studies of these cores will be conducted both by Highway Commission of Kansas and by the University of Illinois. The results of these studies together with the observation of the longtime performance of the bridge decks will be reported at some later date.

Appendix F
Additional Experimental Data

In the previous sections only the average values of the results of the freezing and thawing tests have been discussed. Individual values obtained for each specimen are presented in Figs. F55 through F64.

Additional experimental data from Phase 2, Effectiveness Study, are given in Figs. F67 through F72. These data were of minor significance and, therefore, were not discussed in detail within the main body of this report.

Appendix G

Project Statement

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Highway Research Board
National Academy of Sciences--National Research Council

FY '68

Project Statement

Project: 18-1

Research Project Title:

Revibration of Retarded Concrete for Continuous Bridge Decks

General Problem Area:

Concrete Materials

Research Problem Statement:

Transverse and longitudinal cracking of continuous concrete bridge decks can be caused by changes in deflection and rotation over supports during construction, in addition to the possible effect of restraint to subsidence (bleeding) afforded by the top reinforceing steel. Such cracking is of significance with respect to the development of spalling. Revibration of retarded concrete may be useful in eliminating such occurrences in continuous bridge decks placed in one operation.

Objectives:

1. Conduct a survey to determine the extent to which either delayed vibration or revibration has been used in placing bridge deck concrete. The survey is to include the purpose, conditions, and results.

2. Determine either by laboratory and/or field tests if transverse and longitudinal cracking can be significantly reduced by revibration after retarded concrete has been placed over the entire deck of continuous bridge or a complete segment of several spans supported by a continuous girder system.

3. Determine the effect of revibration and subsequent finishing on the durability of bridge deck surfaces exposed to deicing chemicals.

4. Determine the most effective and practical means of revibration in the field.

Funds Available: $100,00

Completion Time: 18 months

NOTE: The essential features desired in a proposal for research are stated in the National Cooperative Highway Research Program brochure entitled "General Information on Administration and Contracting" dated January 1967 (Revised). Copies available on request.

Authorization to Begin Work: Final award of the contract for this research is expected to be made in the period September 1967-October 1967.

Mail Twenty-Five (25) Copies of Proposal to:

W. A. Goodwin
Program Engineer, NCHRP
Highway Research Board
2101 Consitution Avenue, N. W.
Washington, D. C. 20418

PROPOSAL DEADLINE: Postmarked not later than midnight April 25, 1967, Eastern Standard Time.

TABLES

Table B1: Inquiry on the Use of Revibration in the Construction of Concrete Bridge Decks - Phase 1

Highway Department	Summary of Reply	Special Notes
Alabama	1, 2	
Alaska	1	
Arizona	1, 3	
Arkansas	1, 2	
California	1, 2	
Colorado	1, 2	A concrete bridge deck was caught by earth tremor while setting. No adverse effects have been noticed.
Connecticut	1, 2, 3	
Delaware	1	A field test of revibrated 6 x 16 in. cylinders was conducted in 1957.
District of Columbia	1, 3	
Florida	1, 2, 4	
Georgia	1	
Hawaii	1, 2	
Idaho	1, 2	
Illinois	1, 2	
Indiana	1, 2	
Iowa	1	Retarded concretes are used to allow dead load deflections of continuous structures before setting.
Kansas	1	Starting in November 1967 specifications require revibration of pavements.
Louisiana	1	
Maine	1, 2	
Maryland	1, 2	
Massachusetts	1, 3, 4	
Michigan	1, 2	Retarded concretes are used to allow dead load deflection of continuous structures before setting. An informal experiment indicated internal revibration of retarded concrete was ineffective.
Minnesota	1, 2	
Missouri	1, 2	
Montana	1, 2	
Nebraska	1, 2, 3	
Nevada	1, 2	
New Hampshire	1, 2	
New Jersey	1	
New Mexico	1	
New York	2	Concrete bridge deck was replaced while traffic on other half of bridge caused continuous vibration during setting.

Table B1 (Con't.)

Highway Department	Summary of Reply	Special Notes
North Carolina	1, 2	
North Dakota	1	
Ohio	1, 2	
Oklahoma	1, 2	Department offered to assist Oklahoma State University with similar research project.
Oregon	1, 2	
Pennsylvania	1, 2	
Rhode Island	1, 2	
South Carolina	1	
South Dakota	1, 2	
Tennessee	1	
Texas	1, 2	Retarded concretes are used to allow dead load deflection of continuous structures before setting.
Utah	1, 2	
Vermont	1, 2	
Virginia	1, 2	
Washington	1, 3	A 20 x 20 ft slab was revibrated because of equipment failure. No adverse effects have been noticed.
West Virginia	1, 2	
Wisconsin	1	
Wyoming	1, 2	Retarded concretes are used to allow dead load deflection of continuous structures before setting.
Alberta	1, 2	
New Brunswick	1, 2	
Newfoundland	1	Limited use has been made of revibrated concrete for post tensional concrete girders.
Nova Scotia	1, 2	
Prince Edward Island	1, 2	
Saskatchewan	1	The continuous floor slab of a 3 span structure was placed in one operation using a retarder and delayed vibration.

1. No experience with revibration of retarded concrete bridge decks.
2. No experience with delayed vibration of retarded concrete bridge decks.
3. Specifications do not permit delayed vibration or revibration.
4. Delayed vibration or revibration not being considered.

Table C2a: Effectiveness Study - Phase 2
Description of Specimens in Series P and ACC:
Pilot Studies and Accelerometer Tests

No.	Specimen Designation	Air Content (%) 1st Batch	2nd Batch	Initial Set (hr:min)	Cracking Type	Time After Mixing (hr:min)	Maximum Defl. (in)	Revibration Type	Time After Mixing (hr:min)	Energy Level (%)	Reinforcement According to Fig. C3
1	PT-0	>7	>7	-	-	4:00	1 1/2	Surface	4:00	20	A
2	PT-1	-	-	-	None	-	-	Internal	4:20-7:20	-	A
3	PT-2	>7	5.8	7:40	-	3:00	1 1/2	Surface	3:40	20, 40, 60, 80	A
4	PT-3	>7	>7	7:40	-	2:00	2 1/2	None	-	-	A
5	PT-4	>7	>7	6:20	-	4:00	2 1/4	None	-	-	A
6	PT-5	5.4	5.4	7:30	-	3:00	1 1/2	None	-	-	A
7	APT-1	5.9	5.5	6:30 6:50	-	2:00	3 7/8	Surface	4:00, 5:00, 7:10	20, 80	A
8	APT-2	6.0	5.0	7:50 6.15	-	2:00	3 1/2	None	-	-	A
9	APT-3	4.0	5.0	5:50 5:45	-	2:00	3 1/2	None	-	-	A
7	ACC-1	5.9	5.5	6:30 6:50	-	2:00	3 7/8	Surface	4:00, 5:00, 7:10	20, 80	A
10	ACC-2	6.1	>7	7:00	None	-	-	Surface	4:00, 5:00	20, 80	A
96	ACC-3	7.0	5.5	-	None	-	-	Surface	4:00	80	A

Table C2b: Effectiveness Study - Phase 2
Description of Specimens in Series 1: Method of Revibration, Revibration Energy and Extent of Initial Cracking

No.	Specimen Designation	Air Content (%) 1st Batch	Air Content (%) 2nd Batch	Initial Set (hr:min)	Cracking Type	Cracking Time After Mixing (hr:min)	Cracking Max. Defl. At Midspan (in)	Revibration Type	Revibration Time After Mixing (hr:min)	Revibration Energy Level (%)	Reinforcement According to Fig. C3
11	SU-1-SL-0	5.5	5.5	6:00	Slight	2:00	1 1/4	None	-	-	A
12	SU-1-SL-20	6.3	7.3	6:30	Slight	2:00	1 1/4	Surface	4:00	20	A
13	SU-1-SL-80	6.4	6.3	6:45	Slight	2:00	1 1/4	Surface	4:00	80	A
14	SU-1-ME-0	5.8	4.8	7:45	Medium	2:00	2 1/2	None	-	-	A
15	SU-1-ME-20	6.8	6.9	8:50	Medium	2:00	2 1/2	Surface	4:00	20	A
16	SU-1-ME-80	5.4	5.8	7:15	Medium	2:00	2 1/2	Surface	4:00	80	A
17	SU-1-SE-0	6.7	7.0	7:45	Severe	2:00	3 1/2	None	-	-	A
18	SU-1-SE-20	6.5	6.5	7:45	Severe	2:00	3 1/2	Surface	4:00	20	A
19	SU-1-SE-80	6.2	6.5	5:50	Severe	2:00	3 1/2	Surface	4:00	80	A
20	IN-1-SL-0	7.0	6.3	8:30	Slight	2:00	1/4	None	-	-	A
21	IN-1-SL-20	6.7	6.0	7:15	Slight	2:00	1 1/4	Internal	4:00	Low	A
22	IN-1-SL-80	6.5	6.0	7:00	Slight	2:00	1 1/4	Internal	4:00	High	A
23	IN-1-ME-0	4.8	6.0	6:00	Medium	2:00	2 1/2	None	-	-	A
24	IN-1-ME-20	5.2	5.8	6:45	Medium	2:00	2 1/2	Internal	4:00	Low	A
25	IN-1-ME-80	5.8	6.0	6:45	Medium	2:00	2 1/2	Internal	4:00	High	A
26	IN-1-SE-0	6.5	5.0	8:10	Severe	2:00	3 1/2	None	-	-	A
27	IN-1-SE-20	5.7	6.1	7:30	Severe	2:00	3 1/2	Internal	4:00	Low	A
28	IN-1-SE-80	4.8	5.0	7:05	Severe	2:00	3 1/2	Internal	4:00	High	A

Table C2c: Effectiveness Study - Phase 2
Description of Specimens in Series 2: Time of Revibration

No.	Specimen Designation	Air Content (%) 1st Batch	2nd Batch	Initial Set (hr:min)	Cracking Type	Time After Mixing (hr:min)	Max. Defl. at Midspan (in)	Revibration Type	Time After Mixing (hr:min)	Energy Level (%)	Reinforcement According to Fig. C3
29	SU-2-SE-0	4.5	6.5	7:30	Severe	2:00	3 1/2	None	-	-	A
30	SU-2-SE-20	5.5	5.5	8:05	Severe	2:00	3 1/2	Surface	4:00	20	A
31	SU-2-SE-80	5.5	6.0	9:00	Severe	2:00	3 1/2	Surface	4:00	80	A
35	SU-2-SE-0A	5.7	6.1	9:15	Severe	2:00	3 1/2	None	-	-	A
36	SU-2-SE-20-3	5.8	6.1	8:35	Severe	2:00	3 1/2	Surface	3:00	20	A
37	SU-2-SE-20-7	5.0	5.2	8:15	Severe	2:00	3 1/2	Surface	7:00	20	A
38	SU-2-SE-0-B	5.2	5.0	7:55	Severe	2:00	3 1/2	None	-	-	A
39	SU-2-SE-80-7	5.4	4.8	8:50	Severe	2:00	3 1/2	Surface	7:00	80	A
40	SU-2-SE-80-8 1/2	5.9	6.0	8:20	Severe	2:00	3 1/2	Surface	8:30	80	A
43	SU-2-SE-0C	5.1	6.3	7:15	Severe	2:00	3 1/2	None	-	-	A
44	SU-2-SE-20-5	5.7	5.3	7:50	Severe	2:00	3 1/2	Surface	5:00	20	A
45	SU-2-SE-80-5	5.7	6.1	8:40	Severe	2:00	3 1/2	Surface	5:00	80	A
32	IN-2-SE-0	6.4	6.7	7:45	Severe	2:00	3 1/2	None	-	-	A
33	IN-2-SE-80-2	5.8	6.2	7:30	Severe	2:00	3 1/2	Internal	2:15	High	A
34	IN-2-SE-80-3	7.0	6.7	8:45	Severe	2:00	3 1/2	Internal	3:00	High	A

Table C2d: Effectiveness Study - Phase 2
Description of Specimens in Series 5: Curing Conditions
Prior to Initial Set

No.	Specimen Designation	Air Content (%) 1st Batch	Air Content (%) 2nd Batch	Initial Set (hr:min)	Cracking Type	Cracking Time After Mixing (hr:min)	Cracking Max. Defl. at Midspan (in)	Revibration Type	Revibration Time After Mixing (hr:min)	Revibration Energy Level (%)	Reinforcement According Fig. C3
	Series 3 - Percentage of Reinforcement										
49	SU-3G-SE-0	5.2	5.7	8:05	Severe	2:00	3 1/2	None	-	-	C
50	SU-3G-SE-80	5.5	5.6	7:45	Severe	2:00	3 1/2	Surface	4:00	80	C
51	SU-3L-SE-0	5.5	5.5	7:55	Severe	2:00	3 1/2	None	-	-	B
52	SU-3L-SE-80	5.8	5.3	8:15	Severe	2:00	3 1/2	Surface	4:00	80	B
59	ANCH-1	4.5	6.0	5:30	-	2:00	1 3/4	None	-	-	A*
	Series 4 - Time of Initial Set										
53	SU-4-SL-0	4.0	4.4	3:45	Slight	2:00	1 1/4	None	-	-	A
54	SU-4-SL-20	4.3	3.8	3:45	Slight	2:00	1 1/4	Surface	3:00	20	A
55	SU-4-SL-80	3.5	3.7	3:20	Slight	2:00	1 1/4	Surface	3:00	80	A
56	SU-4-SE-0	7.0	4.2	3:20	Severe	2:00	3 1/2	None	-	-	A
57	SU-4-SE-20	4.5	4.6	3:25	Severe	2:00	3 1/2	Surface	3:00	20	A
58	SU-4-SE-80	4.9	6.1	3:45	Severe	2:00	3 1/2	Surface	3:00	80	A

*Ends of the longitudinal reinforcement were anchored to the formwork.

Table C2e: Effectiveness Study - Phase 2
Description of Specimens in Series 5: Curing Conditions
Prior to Initial Set

No.	Specimen Designation	Air Content (%)		Initial Set (hr:min)	Revibration			Heating	
		1st Batch	2nd Batch		Type	Time After Mixing (hr:min)	Energy Level (%)	Surface Temperature, ^{o}F	Distance of Lamp From Surface, in.
63	SU-5-NO-0	6.8	6.9	7:35	None	-	-	110	3
66	SU-5-NO-0A	5.8	5.8	7:15	None	-	-	110	9
71	SU-5-NO-80	6.5	6.3	8:00	Surface	0:45	80	110	9
78	SU-5-NO-0B	6.6	6.8	7:05	None	-	-	95	12
85	SU-5-NO-80B	6.0	6.0	7:15	Surface	1:30	80	95	12

Reinforcement: Type A according to Fig. C3

No Flexural Cracking

Table C2f: Effectiveness Study - Phase 2
Description of Specimens in Series 7: Effectiveness of Revibration in Closing Plane of Weakness Cracks

No.	Specimen Designation	Air Content (%) 1st Batch	Air Content (%) 2nd Batch	Initial Set (hr:min)	Cracking: Type	Cracking: Time After Mixing (hr:min)	Cracking: Max. Defl. at Midspan (in)	Upward Deflection of Reinforcement (in)	Revibration: Type	Revibration: Time After Mixing (hr:min)	Revibration: Energy Level (%)	Revibration According to Fig. C3
46	SU-7-T-M-2	5.6	5.8	7:50	Medium	2:00	2 1/2	0.08	None	-	-	A
47	SU-7-T-M-4	5.8	5.6	9:35	Medium	2:00	2 1/2	0.16	None	-	-	A
48	SU-7-T-M-6	5.7	5.9	7:40	Medium	2:00	2 1/2	0.24	None	-	-	A
67	SU-7-SE-0-2	6.7	6.1	7:40	Severe	2:00	3 1/2	0.08	None	-	-	A
68	SU-7-SE-80-2	6.9	6.1	7:40	Severe	2:00	3 1/2	0.08	Surface	4:00	80	A
86	SU-7-SE-50-2	6.0	5.4	7:05	Severe	2:00	3 1/2	0.08	Surface	4:00	50	A
69	SU-7-SE-0-1	7.0	6.5	8:00	Severe	2:00	3 1/2	0.04	None	-	-	A
70	SU-7-SE-80-1	7.0	6.9	8:00	Severe	2:00	3 1/2	0.04	Surface	4:00	80	A

Table C2g: Effectiveness Study - Phase 2
Description of Specimens in Series 8, 9 and 10:
Deflection at Later Age, Direction of Revibration and
Effect of Revibration on Air Content Distribution
and Abrasion Resistance

No.	Specimen Designation	Air Content (%) 1st Batch	Air Content (%) 2nd Batch	Initial Set (hr:min)	Cracking Type	Cracking Time After Mixing (hr:min)	Cracking Max. Defl. At Midspan (in)	Revibration Type	Revibration Time After Mixing (hr:min)	Revibration Energy Level (%)	Reinforcement According to Fig. C3
Series 8 - Deflection at Later Age											
72	SU-8-SE-0	6.7	5.5	6:50	Severe	4:30	3 1/2	None	-	-	A
73	SU-8-SE-20	6.3	6.5	7:35	Severe	4:30	3 1/2	Surface	5:00	20	A
74	SU-8-SE-80	6.0	6.1	6:50	Severe	4:30	3 1/2	Surface	5:00	80	A
Series 9 - Direction of Revibration											
75	SU-9-SE-0	5.9	6.2	7:40	Severe	2:00	3 1/2	None	-	-	A
76	SU-9-SE-80P	6.3	6.3	7:20	Severe	2:00	3 1/2	Surface	4:00	80	A
77	SU-9-SE-80V	6.2	6.1	6:35	Severe	2:00	3 1/2	Surface	4:00	80	A
83	SU-9-SE-50P	6.6	6.2	6:50	Severe	2:00	3 1/2	Surface	4:00	50	A
84	SU-9-SE-50V	5.2	5.0	6:00	Severe	2:00	3 1/2	Surface	4:00	50	A
Series 10 - Effect of Revibration on Air Content Distribution and Abrasion Resistance											
87	SU-10-NO-20	6.1	5.4	7:05	None	-	-	Surface	4:00	20	A
88	SU-10-NO-80	5.8	6.0	6:35	None	-	-	Surface	4:00	80	A
89	SU-10-NO-50	6.7	5.8	7:15	None	-	-	Surface	4:00	50	A

Table C3: Properties of Aggregates Used in the Laboratory Studies

Type	Cumulative Percent Passing										Fineness Modulus	Bulk Spec. Gravity SSD
	1 in.	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100		
Sand	100	100	100	100	100	92	74	43	14	3	2.74	2.60
Coarse Aggregate	98	87	42	14	4	-	-	-	-	-	6.97	2.66

Table C4: Average and Maximum Crack Width, and Crack Spacing in Deflected Concrete Slabs
Phase 2 - Series P

Deflection in.	Time of Deflection: 2 Hours After Casting			3 Hours After Casting			4 Hours After Casting		
	max crack width in.	av crack width in.	av crack spacing in.	max crack width in.	av crack width in.	av crack spacing in.	max crack width in.	av crack width in.	av crack spacing in.
1/2	0.001	0.0005	8	0.001	0.0005	10	0.0005	0.0005	9
1	0.002	0.001	7	0.002	0.001	5	0.005	0.001	7
1-1/2	0.005	0.002	-	0.005	0.002	-	0.008	0.002	-
2	0.008	0.002	3	0.006	0.002	2	0.010	0.004	2
2-1/2	0.015	0.003	-	0.007	0.003	-	0.020	0.008	-
3	0.020	0.004	2	0.008	0.004	2	0.040	0.009	2
3-1/2	0.040	0.005	1	0.009	0.005	-	0.050	0.010	-
4	-	-	-	0.010	0.007	-	0.050	0.010	-

Table C5: Effect of Surface Revibration on Unit Weight, Compressive Strength and Relative Dynamic Modulus of Concrete Slabs Phase 2 - Series 1

Slab -	Revibration %	Unit Weight lbs/ft^3	From Cores: Compressive Strength psi	From Pulse Velocity: Relative Dynamic Modulus of Elasticity*** -
SUI-SE-0	none	142.4*	5800*	1.00**
SUI-SE-20	20	141.4	5760	0.98
SUI-SE-80	80	143.5	6050	1.06
SUI-ME-0	none	-	0-	1.00
SUI-ME-20	20	-	-	1.04
SUI-ME-80	80	-	-	1.08
SUI-SL-0	none	-	-	1.00
SUI-SL-20	20	-	-	0.96
SUI-SL-80	80	-	-	1.06

*average of 6 values
**average of 21 readings
***The relative dynamic modulus of elasticity given above corresponds to the ratio of V_n^2/V_i^2 where V_n is the sonic velocity determined for the slab in question while V_i is the average sonic velocity through the non-revibrated slab within each group.

Table C6: Effect of Surface Revibration on Air Void Characteristics of Concrete
Phase 2 - Series 10

Specimen -	Section -	Distance From Bottom in.	Revibration %	Air Content No Rev. %	Air Content Rev. %	Paste Content No Rev. %	Paste Content Rev. %	Spacing Factor No Rev. in.	Spacing Factor Rev. in.
SU-10-NO-20	A	6.00	20	4.02	3.51	35.0	38.2	0.0068	0.0074
	B	5.75		5.50	5.10	22.1	29.2	0.0064	0.0058
	C	5.50		6.22	5.82	20.0	18.4	0.0062	0.0068
	D	5.25		5.90	6.18	24.9	27.1	0.0066	0.0061
	E	5.00		5.55	5.82	23.8	25.2	0.0070	0.0074
	F	3.00		5.38	5.18	24.4	22.3	0.0066	0.0063
	G	1.00		5.38	5.88	22.0	24.2	0.0073	0.0069
Air Content From Pressure Method:			6.10%						
SU-10-NO-50	A	6.00	50	4.62	2.93	38.7	43.4	0.0067	0.0078
	B	5.75		4.93	4.24	20.5	22.8	0.0069	0.0068
	C	5.50		4.40	5.58	23.3	23.9	0.0068	0.0057
	D	5.25		4.24	4.56	24.4	23.3	0.0088	0.0066
	E	5.00		3.99	4.30	21.3	22.6	0.0078	0.0066
	F	3.00		5.44	4.12	25.6	25.2	0.0063	0.0083
	G	1.00		6.35	5.00	31.2	24.7	0.0061	0.0072
Air Content From Pressure Method:			5.8%						
SU-10-NO-80	A	6.00	80	3.20	3.00	35.5	41.6	0.0073	0.0079
	B	5.75		4.15	4.50	23.6	26.6	0.0088	0.0059
	C	5.50		3.65	5.25	22.6	25.8	0.0074	0.0053
	D	5.25		4.10	4.40	24.4	23.2	0.0079	0.0067
	E	5.00		4.60	4.75	25.6	24.2	0.0060	0.0069
	F	3.00		4.90	4.50	24.1	23.2	0.0076	0.0074
	G	1.00		4.36	4.35	25.3	21.4	0.0069	0.0068
Air Content From Pressure Method:			5.8%						

Table C7a: Effect of External Revibration on Air Void Characteristics of Concrete
Phase 3a - Series 1A and Series 2C

Section	Distance From Bottom in.	Series 1A Normal Air - Retarder: Air Content No Rev. %	Air Content Rev. %	Paste Content No Rev. %	Paste Content Rev. %	Spacing Factor No Rev. in.	Spacing Factor Rev. in.	Series 2C Normal Air - No Retarder: Air Content No Rev. %	Air Content Rev. %	Paste Content No Rev. %	Paste Content Rev. %	Spacing Factor No Rev. in.	Spacing Factor Rev. in.
		*	**	*	**	*	**	+	++	+	++	+	++
A	6.00	3.85	5.00	30.7	29.5	0.0070	0.0069	4.0	4.6	32.0	31.8	0.0064	0.0066
C	5.50	-	5.15	-	21.9	-	0.0071	-	-	-	-		
D	5.25	-	5.05	-	26.8	-	0.0073	-	-	-	-		
E	5.00	5.82	5.60	21.0	22.4	0.0077	0.0072	5.2	5.8	20.9	23.1	0.0059	0.0056
F	3.00	6.20	5.10	25.3	24.3	0.0072	0.0075	5.4	6.0	24.4	24.6	0.0059	0.0062
G	1.00	6.10	5.56	26.6	23.0	0.0065	0.0070	6.1	6.0	25.2	21.0	0.0060	0.0064
Average Air Content, % From Pressure Method		5.8	6.3					6.5	6.4				

*Specimen 1A-4-8
**Specimen 1A-1-7; T_1 = 2 hours; e_2 = 25 sec.
+Specimen 2C-1-8
++Specimen 2C-2-1; T_1 = 2 hours e_2 = 25 sec.

Table C7b: Effect of External Revibration on Air Void Characteristics of Concrete
Phase 3a - Series 2A and 2B

Section	Distance From Bottom in.	Series 2A Low Air - Retarder						Series 2B Low Air - No Retarder					
		Air Content		Paste Content		Spacing Factor		Air Content		Paste Content		Spacing Factor	
		No Rev. %	Rev. %	No Rev. %	Rev. %	No Rev. in.	Rev. in.	No Rev. %	Rev. %	No Rev. %	Rev. %	No Rev. in.	Rev. in.
		*	**	*	**	*	**	+	++	+	++	+	++
A	6.00	3.1	2.9	29.1	30.2	0.0094	0.0114	2.9	2.7	31.0	29.9	0.0089	0.0100
E	5.00	3.7	4.4	23.1	24.1	0.0114	0.0112	3.9	3.6	22.7	23.0	0.0123	0.0104
F	3.00	4.2	3.8	24.5	23.9	0.0123	0.0092	3.3	3.4	24.6	22.7	0.00117	0.0117
G	1.00	4.1	4.0	22.9	22.0	0.0096	0.00122	3.3	3.9	23.0	23.7	0.00137	0.0094
Average Air Content, % From Pressure Method		4.5	4.9					4.4	4.5				

*Specimen 2A-3-8
**Specimen 2A-2-6; T_2 = 4 hours; e_2 = 25 sec.
+Specimen 2B-1-7
++Specimen 2B-2-2; T_2 = 4 hours; e_2 = 25 sec.

Table D8: Durability Studies - Phase 3a
Description of Specimens

Series	Batch	Air Content %	Retarder	Reinforced	Time of Revibration, T and Duration of Revibration, e for Specimen No. 1	2	3	4	5	6	7	8	Initial Set (Hours)	f'_c 28 (psi)
1A	1	6.3	yes	yes	C	T_1; e_3	T_2; e_3	T_3; e_1	T_3; e_2	T_3; e_3	T_1; e_2	-	8:10	5650
	2	6.5			T_1; e_3	C	T_2; e_3	T_3; e_1	T_3; e_2	T_3; e_3	T_2; e_2	-	8:20	4950
	3	5.5			T_1; e_3	T_2; e_3	C	T_3; e_1	T_3; e_2	T_3; e_3	T_1; e_1	-	8:10	5760
	4	5.8			T_1; e_1	T_1; e_2	T_2; e_3	C	T_1; e_3	T_2; e_1	T_2; e_2	C	-	5880
	5	6.3			T_2; e_1	T_2; e_1	T_2; e_2	T_1; e_1	C	T_1; e_2	C	-	6:00	4410
2A	1	5.7	yes	yes	C	T_1; e_1	T_2; e_1	C	T_2; e_2	T_1; e_1	T_2; e_1	-	6:50	5700
	2	4.9			T_1; e_2	T_2; e_2	T_1; e_1	T_2; e_1	T_1; e_2	T_2; e_2	T_1; e_2	-	6:40	6255
	3	4.5			C	T_1; e_1	T_2; e_1	T_1; e_2	T_2; e_2	T_1; e_1	T_2; e_1	C	-	5680
2B	1	4.4	no	yes	C	T_1; e_1	C	T_1; e_2	C	T_1; e_1	C	-	3:45	4950
	2	4.5			T_1; e_2	T_2; e_2	T_1; e_1	C	T_1; e_2	C	C	-	3:30	5210
2C	1	6.5	no	yes	C	T_1; e_1	T_2; e_1	T_1; e_2	T_2; e_2	T_1; e_1	T_2; e_1	C	3:45	4240
	2	6.4			T_1; e_2	T_2; e_2	T_1; e_1	T_2; e_1	T_1; e_2	T_2; e_2	C	-	-	3900
3	1	5.8	yes	no	C	T_1; e_1	T_2; e_1	T_1; e_2	T_2; e_2	T_1; e_1	T_2; e_1	-	8:00	5650
	2	5.8			T_1; e_2	T_2; e_2	T_1; e_1	T_2; e_1	T_1; e_2	T_2; e_2	C	-	8:20	5580

Time of Revibration

T_1 = 2 hrs. after casting
T_2 = 4 hrs.
T_3 = 5 hrs.

Duration of Revibration

e_1 = 10 sec.
e_2 = 25 sec.
e_3 = 40 sec.

Table D9a: Durability Studies - Phase 3b
Description of Specimens
Series 5D: Finishing Procedures

No.	Specimen Designation	Air Content (%) 1st Batch	Air Content (%) 2nd Batch	Initial Set (hr:min)	Cracking: Type	Cracking: Time After Mixing (hr:min)	Cracking: Max. Defl. at Midspan (in)	Revibration: Type	Revibration: Time After Mixing (hr:min)	Revibration: Energy Level (%)	$f'_{c\,28}$ (psi)
Series 1D-Revibration Energy and Extent of Initial Cracking											
41	SUD-SL-0	5.7	5.7	7:30	Slight	2:00	1 1/4	None	-	-	-
42	SUD-SL-0	5.5	5.5	7:00	Slight	2:00	1 1/4	Surface	4:00	20	-
60	SUD-SE-0	5.9	6.3	5:55	Severe	2:00	3 1/2	None	-	-	5250
61	SUD-SE-80	6.0	6.6	5:30	Severe	2:00	3 1/2	Surface	4:00	80	5420
64	SUD-SE-0	5.9	5.8	7:00	Severe	2:00	3 1/2	None	-	-	5700
65	SUD-SE-80	6.8	6.4	7:20	Severe	2:00	3 1/2	Surface	4:00	80	5780
94	SUD-SE-0A	6.0	6.3	6:30	Severe	2:00	3 1/2	None	-	-	5210
95	SUD-SE-80A	6.0	6.5	6:45	Severe	2:00	3 1/2	Surface	4:00	80	5700
Series 2D-Time of Initial Set											
79	SU-4D-SE-0	6.0	6.2	3:15	Severe	2:00	3 1/2	None	-	-	4740
80	SU-4D-SE-80	5.9	5.5	3:30	Severe	2:00	3 1/2	Surface	3:00	80	4490
90	SLD-RET	6.6	6.6	7:15	None	-	-	None	-	-	5660
91	SLD-NON	6.9	6.8	4:10	None	-	-	None	-	-	4070
Series 3D-Effect of Plane of Weakness Cracks											
81	SU-7D-SE-0-2	6.1	6.3	6:30	Severe & Horizontal	2:00	3 1/2	None	-	-	5560
82	SU-7D-SE-80-2	6.5	7.0	6:20	Severe & Horizontal	2:00	3 1/2	Surface	4:00	80	5100
Series 4D-Effect of Air Content											
98	SDH-FIN-0	8.0	8.0	-	Severe	2:00	3 1/2	None	-	-	4850
99	SDH-STR-80	7.8	8.4	7:15	None	-	-	Surface	4:00	80	4900

Table D9b: Durability Studies - Phase 3b
Description of Specimens
Series 5D: Finishing Procedures

No.	Specimen Designation	Air Content (%) 1st Batch	Air Content (%) 2nd Batch	Initial Set (hr:min)	Cracking Type	Cracking Time After Mixing (hr:min)	Cracking Max. Defl. at Midspan (in)	Revibration Type	Revibration Time After Mixing (hr:min)	Revibration Energy Level (%)	Finishing	f'_{c28} (psi)
92	SU-D-STR-0	6.1	6.4	6:30	None	-	-	None	-	-	None	5410
93	SU-D-STR-80	6.7	6.3	7:05	None	-	-	Surface	4:00	80	None	5780
97	SDN-STR-80	6.0	6.4	6:55	None	-	-	Surface	4:00	80	None	5320
100	SU-D-SE-0-LF	5.8	6.2	8:15	None	-	-	None	-	-	After 4 1/2 Hours	5520
101	SU-D-SE-80-LF	6.8	6.5	8:15	Severe	4:00	3 1/2	Surface	4:20	80	After Revibration	5410

Table D10: Effect of Surface Revibration on Abrasion Resistance of Concrete Phase 2 - Series 10

Air Content %	Revibration %	Abrasion Coefficient* cm^3/cm^2
6.1	--	1.98
6.1	20	1.95
5.8	--	1.54
5.8	50	1.52
6.7	--	2.02
6.7	80	2.09

*Defined as the ratio of the volume of abraded material to the area of the abraded surface.

Table E11: Properties of Field Concrete
Phase 4

Bridge Site	Mix Proportions: Water lbs/yd^3	Mix Proportions: Cement lbs/yd^3	Mix Proportions: Sand lbs/yd^3	Mix Proportions: Gravel lbs/yd^3	Mix Proportions: Retarder	Type of Cement	Max. Aggregate Size in.	Slump in.	Initial Set hours	Air Content %	f'_{c28} psi
Illinois	216	602	1148	899	yes	I	1 1/2	2 - 2.5	2:40	4.0 - 4.5	-
Kansas I	283	639	1884	928	no	II	3/4	1 1/4 - 3 1/4	2:50	4.9 - 6.7	5130
Kansas II	287	647	1952	834	yes	II	3/4	2 - 4	5:00	4.2 - 5.4	6520

FIGURES

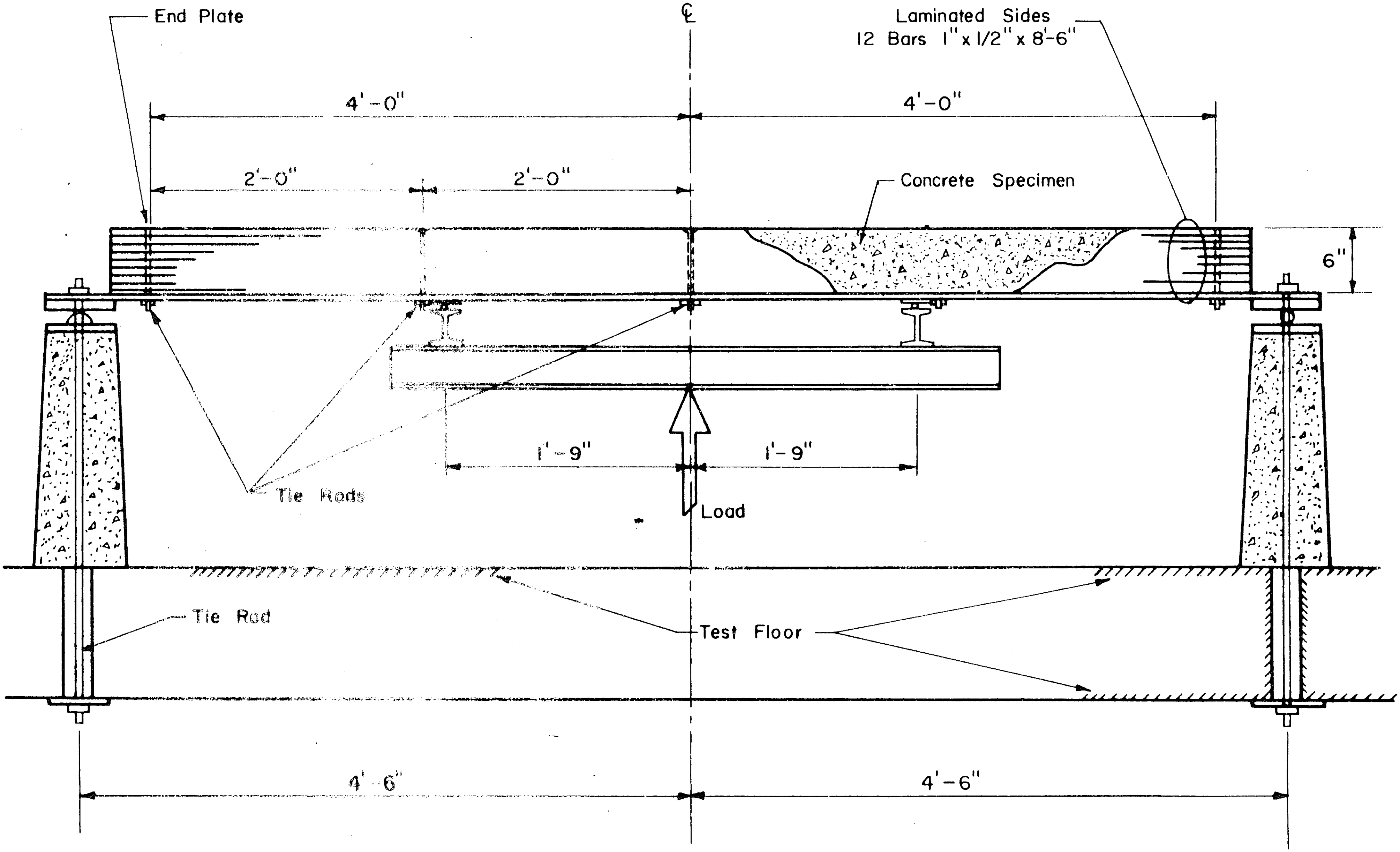


FIG. C2 EXPERIMENTAL SET-UP FOR DEFLECTION OF FRESH CONCRETE SLABS IN FORMWORK

Dear Sir:

We have submitted a research proposal for Highway Research Board NCHRP Project 18-1: REVIBRATION OF RETARDED CONCRETE FOR BRIDGE DECKS+

In this connection, we would like to ascertain the extent to which either delayed vibration or revibration has been used in placing bridge deck concrete. I would therefore appreciate hearing of any such experience your state may have had or if you know of anyone who has had such experience, along with any references you may know of.

If you have used delayed vibration or revibration, please describe your purpose, the methods and procedures employed, details of the structure, the schedule of concrete placement, the properties of the fresh concrete if available, the kind and amount of any admixture used, temperature, humidity, and wind conditions if known, and your evaluation of the results.

I recognize that this request is an imposition; your cooperation will therefore be doubly appreciated.

Sincerely yours,

FIG. B1. SAMPLE LETTER USED IN INQUIRY ON THE USE OF REVIBRATION IN BRIDGE DECK CONSTRUCTION - Phase 1

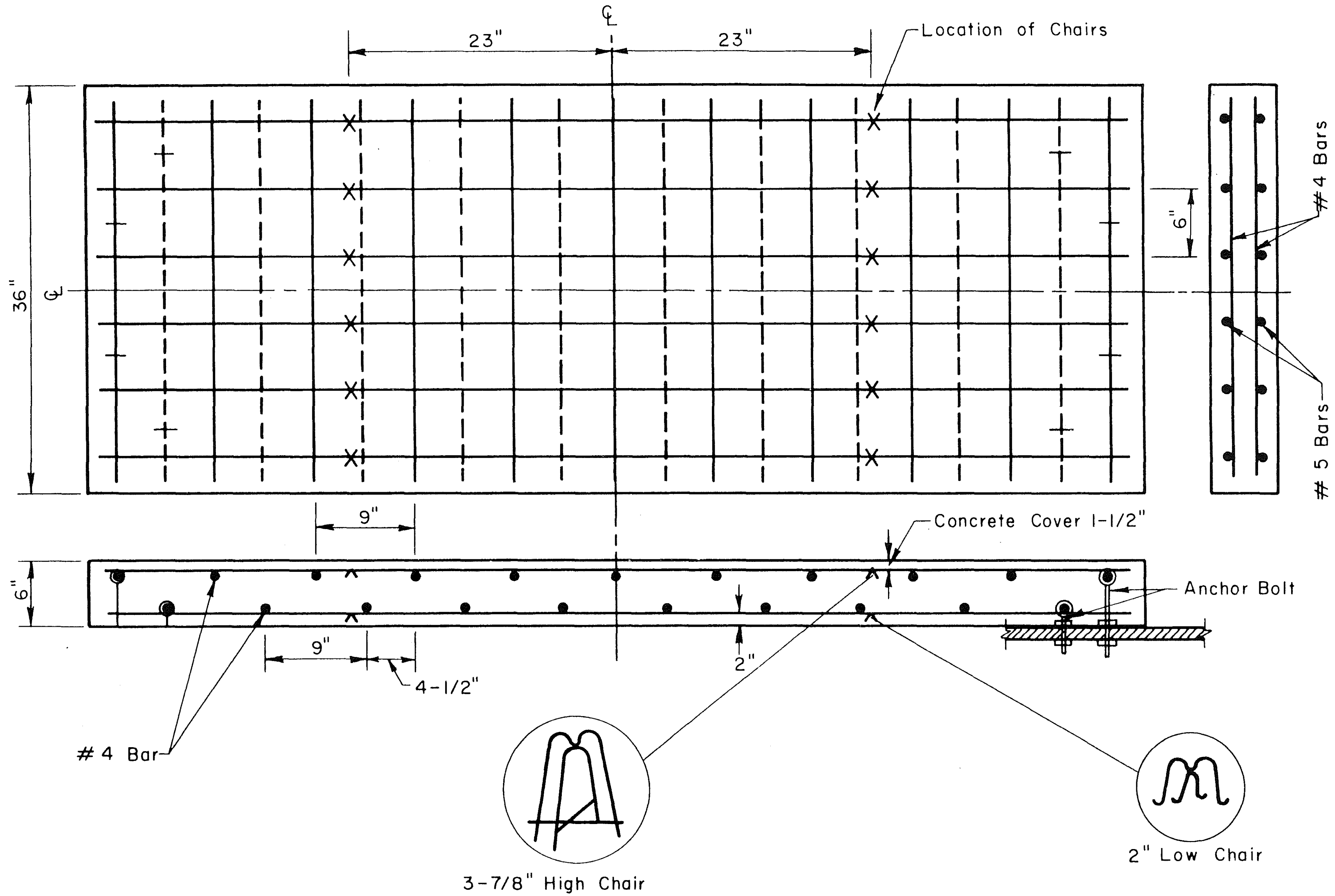


FIG. C3a LAYOUT OF REINFORCEMENT — TYPE A — PHASE 2

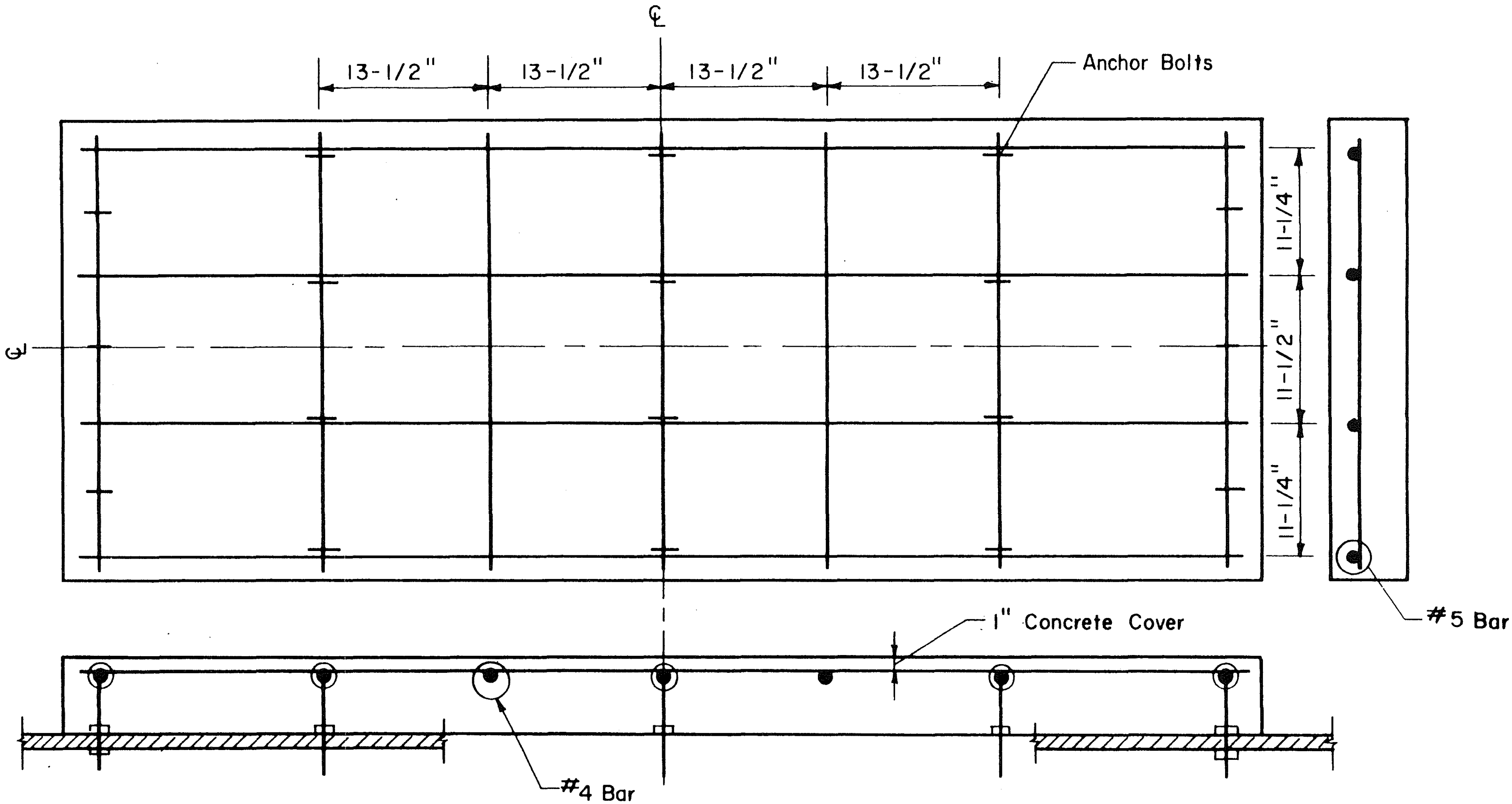


FIG. C3b LAYOUT OF REINFORCEMENT – TYPE B – PHASE 2

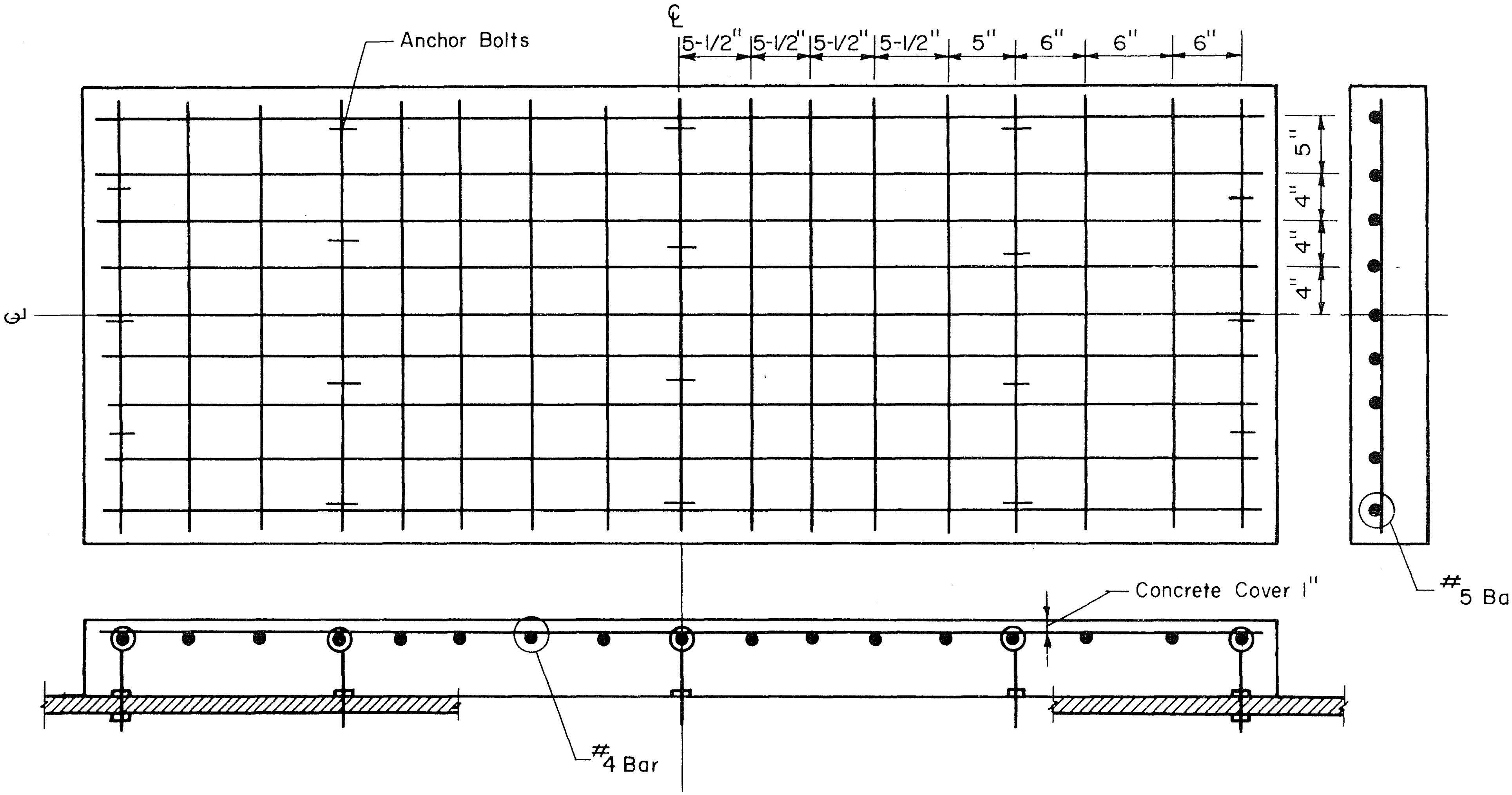


FIG. C3c LAYOUT OF REINFORCEMENT – TYPE C – PHASE 2

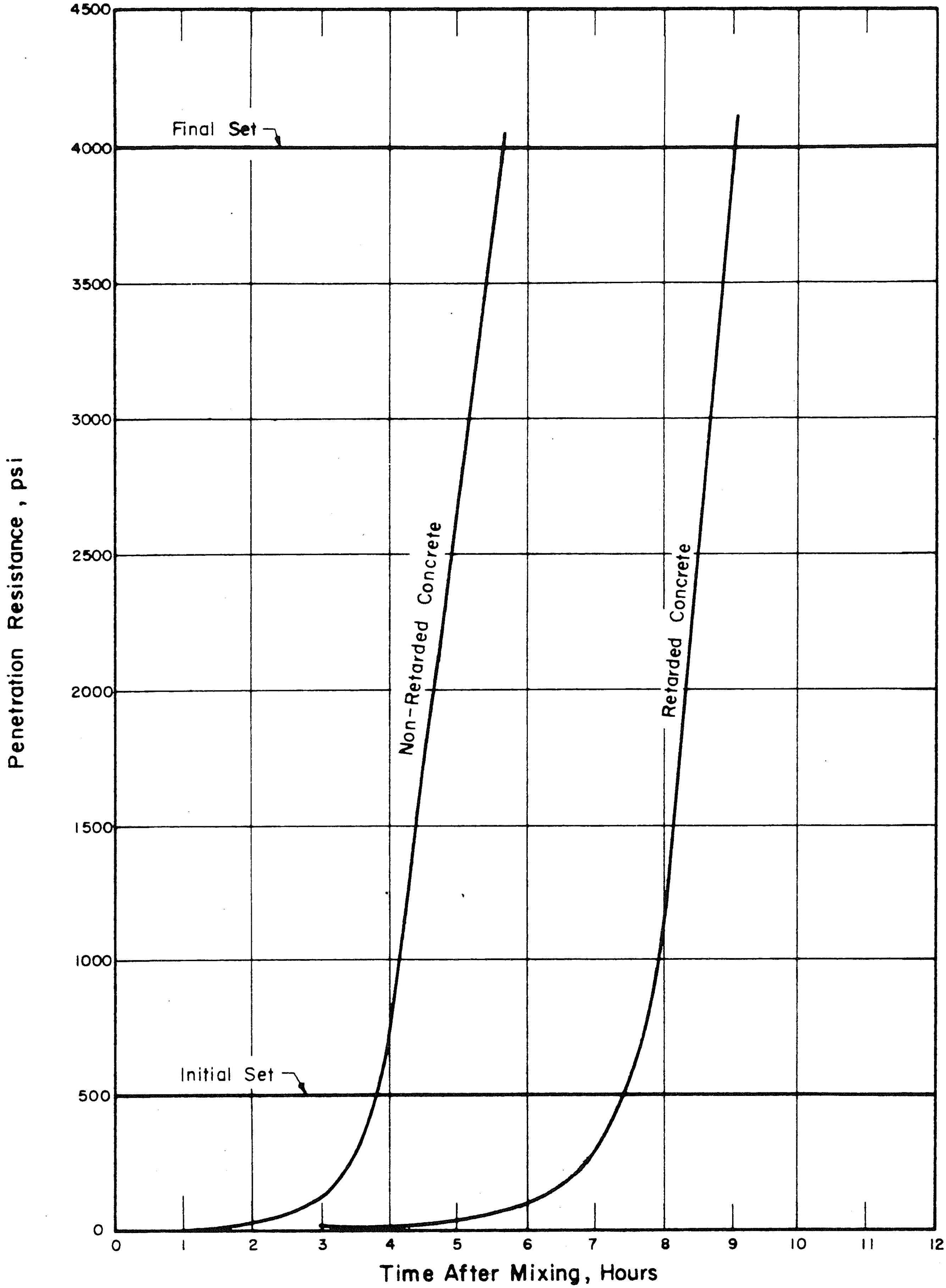


FIG. C4 TYPICAL RESULTS FROM PENETRATION TEST OF RETARDED AND NON-RETARDED CONCRETE

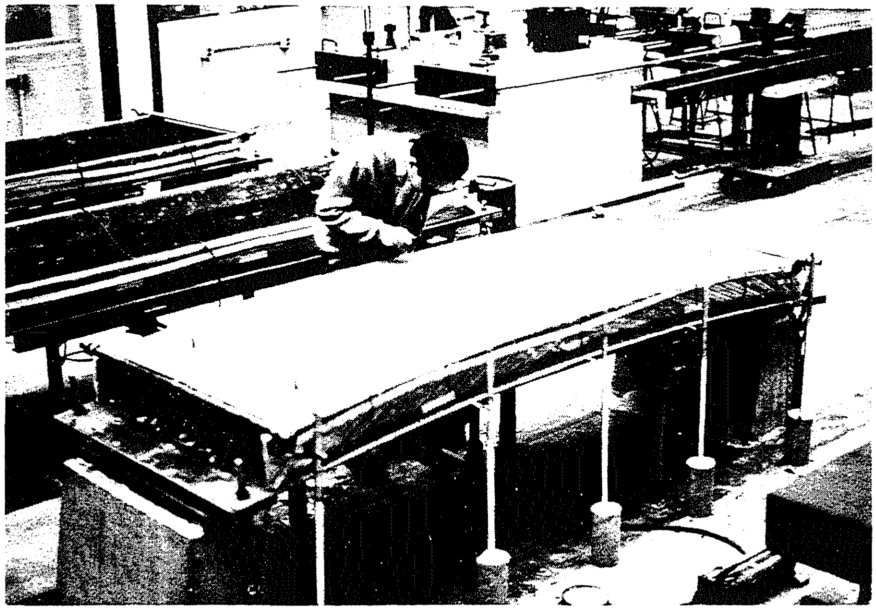


FIG. C5 DEFLECTED SLAB AND FORMWORK — PHASES 2 AND 3

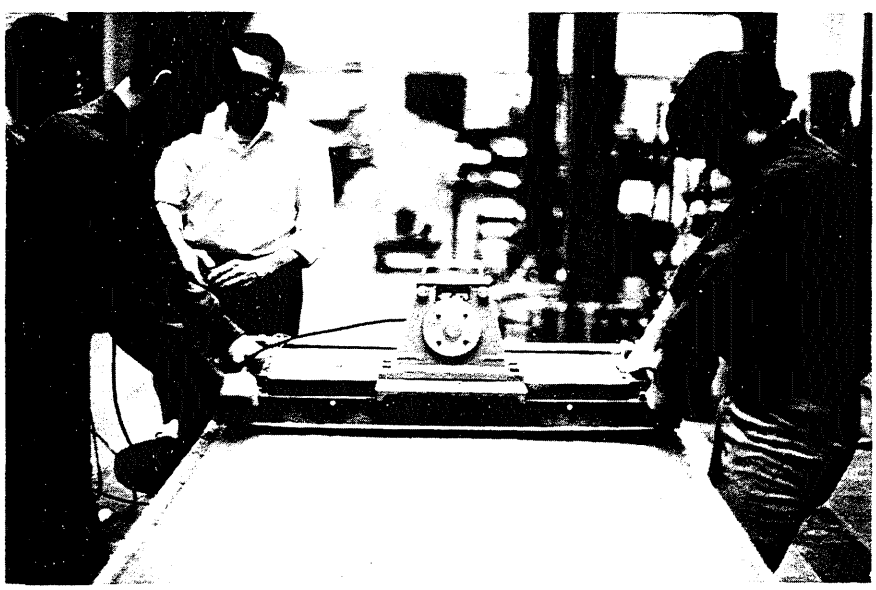


FIG. C6 SURFACE SCREED FOR REVIBRATION OF REINFORCED CONCRETE SLABS

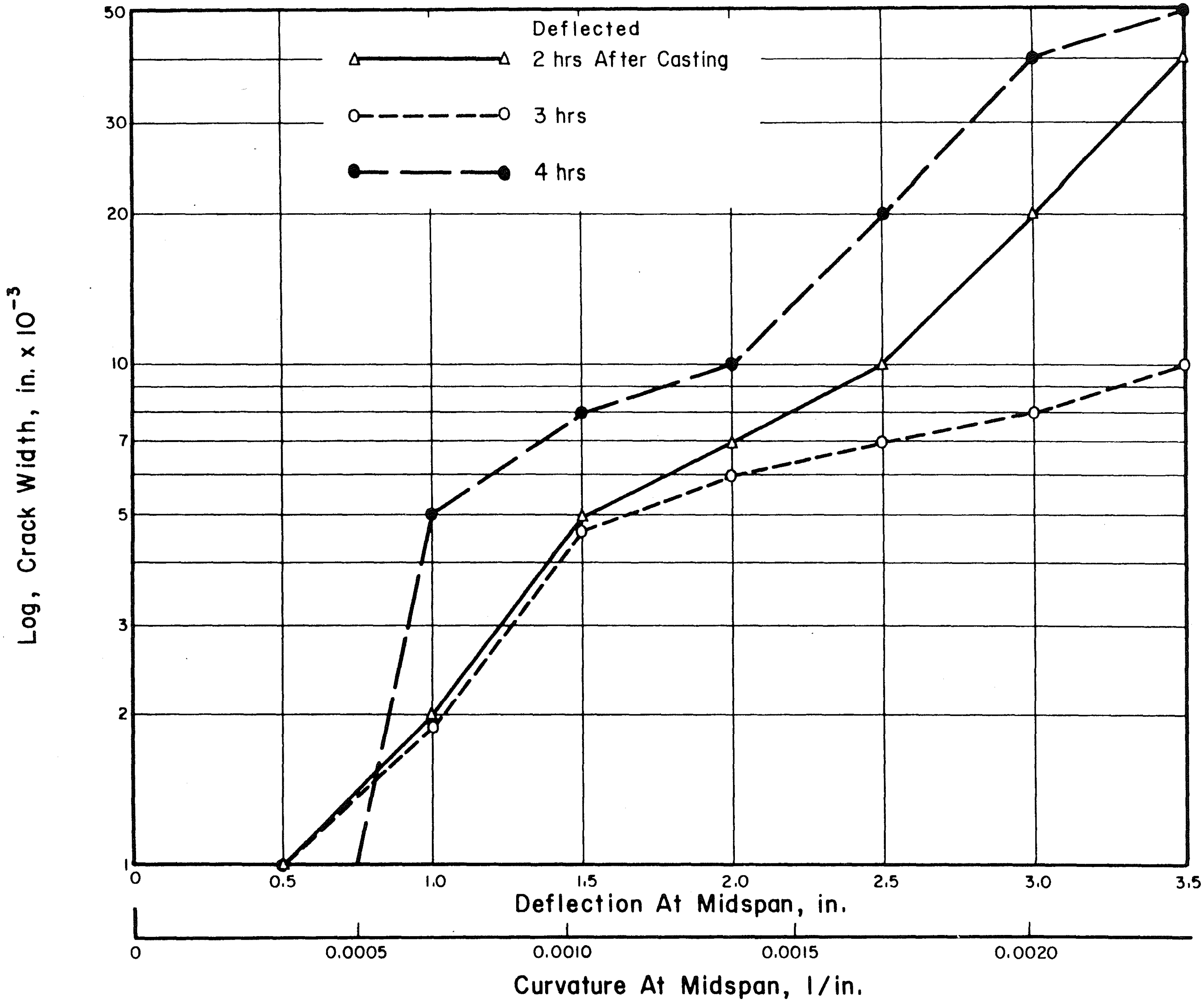


FIG. C7 MAXIMUM CRACK WIDTH IN CONCRETE SLABS DEFLECTED 2; 3 OR 4 HOURS AFTER MIXING—TEST SERIES P—PHASE 2

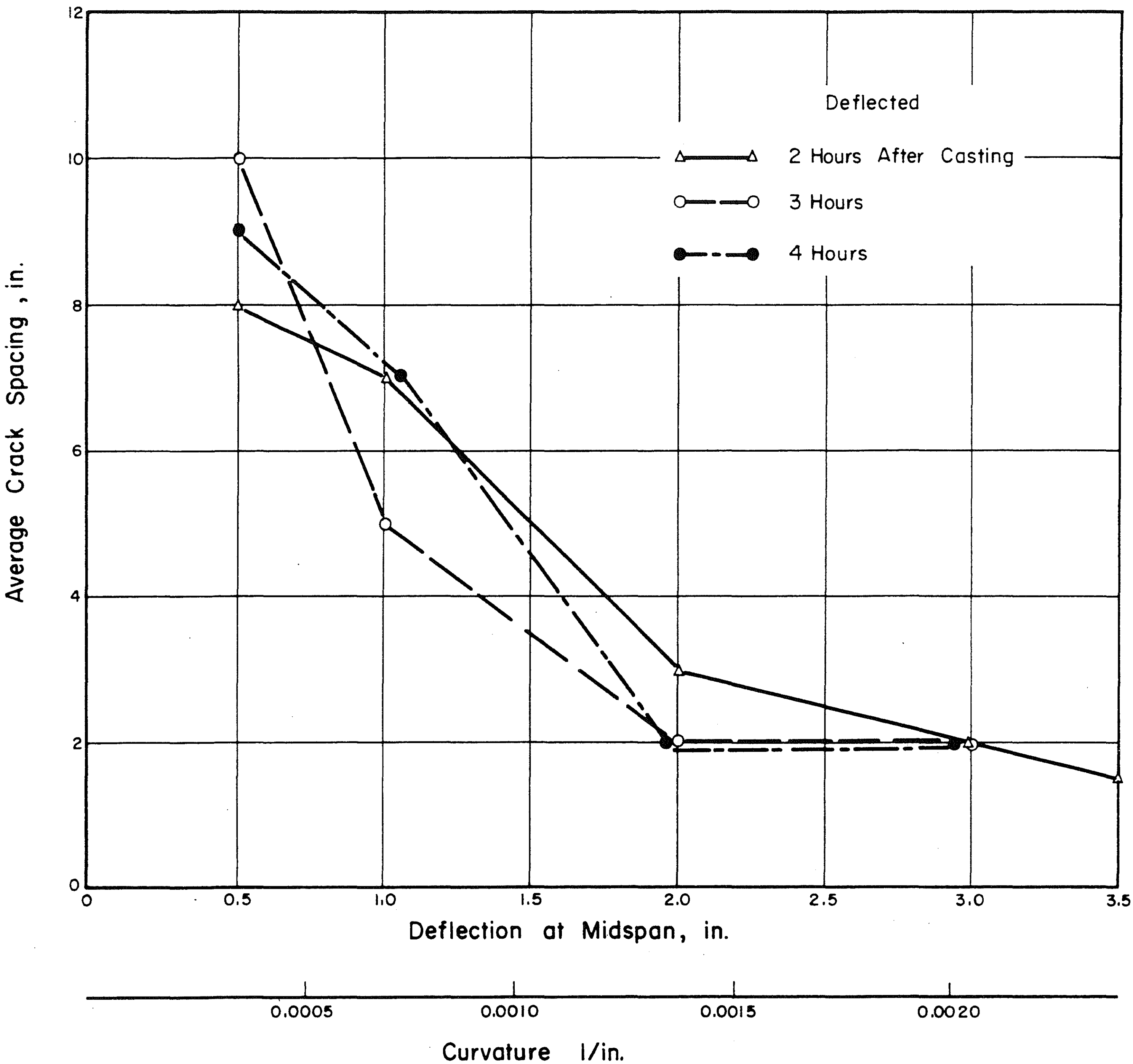
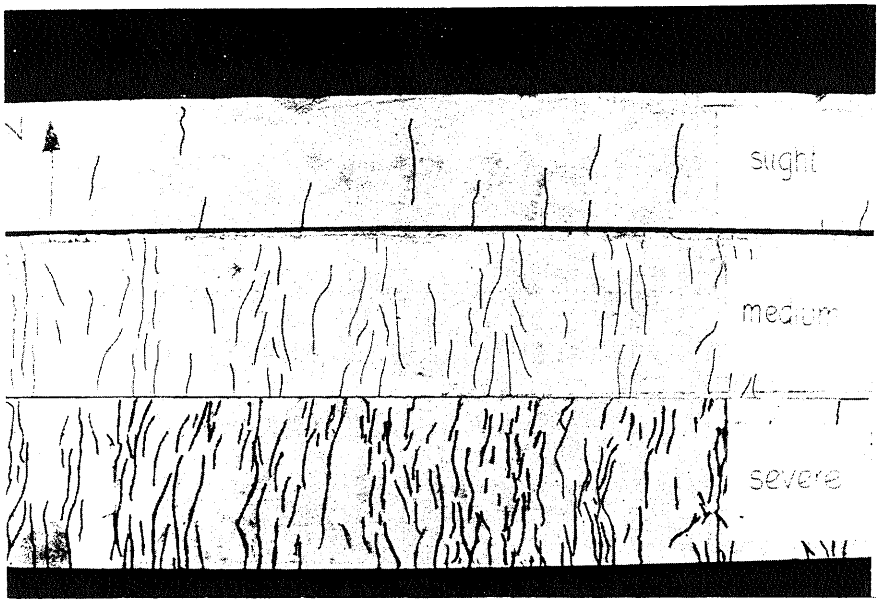


FIG. C8 AVERAGE CRACK SPACING IN CONCRETE SLAB DEFLECTED 2 : 3 or 4 HOURS AFTER CASTING; TEST SERIES P — PHASE 2



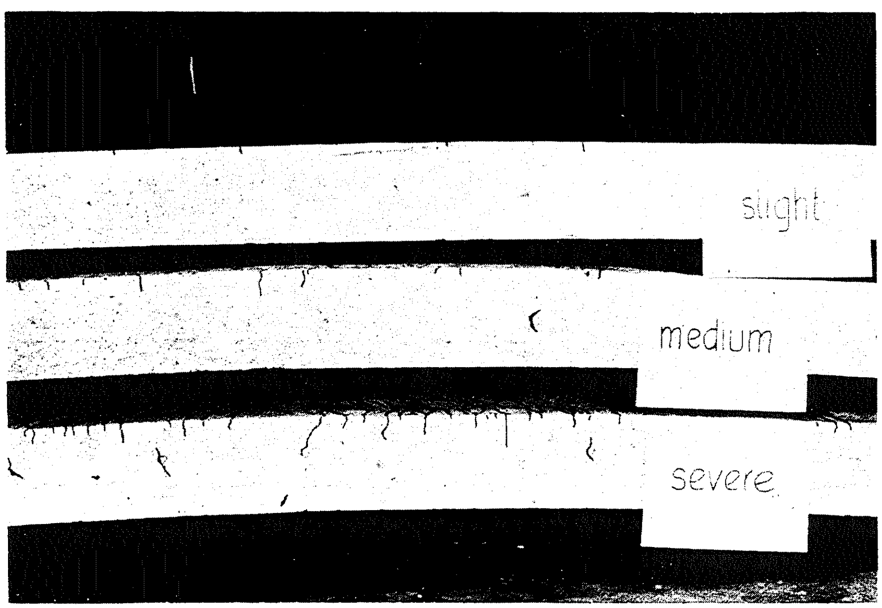
Deflection

0.5 in.

2.0 in.

3.5 in.

FIG. C 9 CRACK PATTERNS ON CONCRETE SURFACE



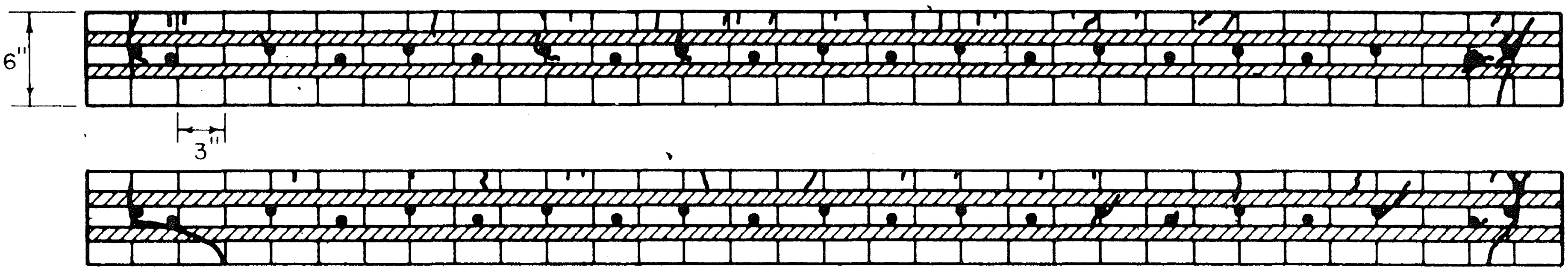
Deflection

0.5 in.

2.0 in.

3.5 in.

FIG. C 10 SECTIONS OF CRACKED CONCRETE SLABS



Severe Deflection After 2 Hours Specimen SU-2-SE-O; Series 2

Severe Deflection After 4-1/2 Hours Specimen SU-8-SE-O; Series 8

FIG. C11 SECTIONS OF SEVERELY CRACKED CONCRETE SLABS; TIME OF DEFLECTION: 2 HOURS AND 4-1/2 HOURS AFTER MIXING

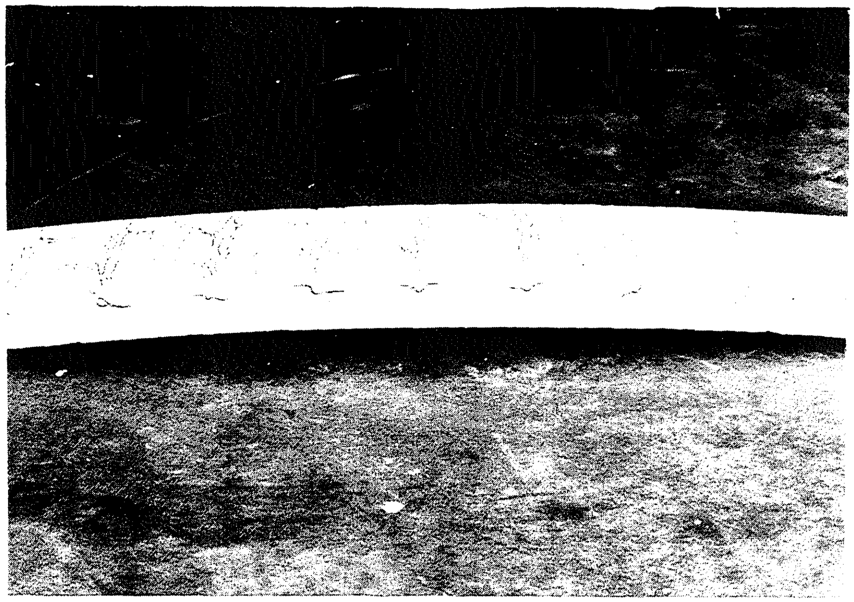


FIG. C 12 CONCRETE SLABS WITH ARTIFICIAL "PLANE OF WEAKNESS" CRACKS

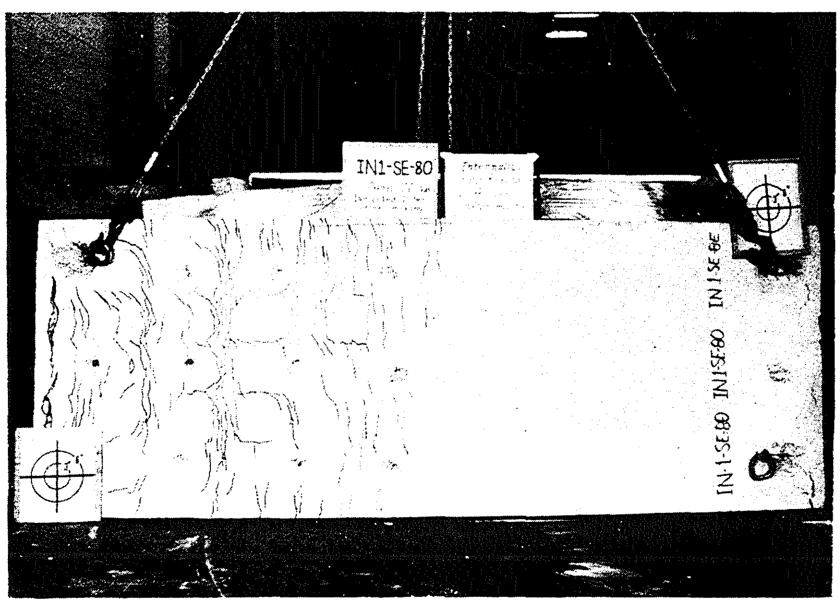
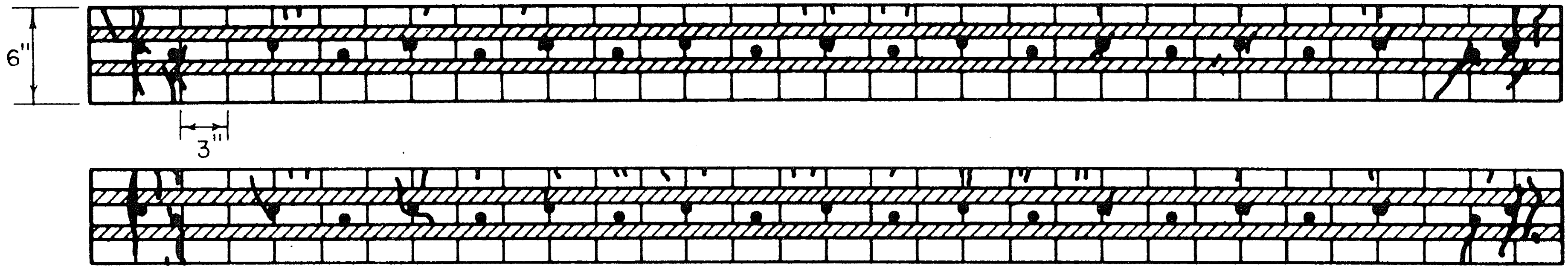
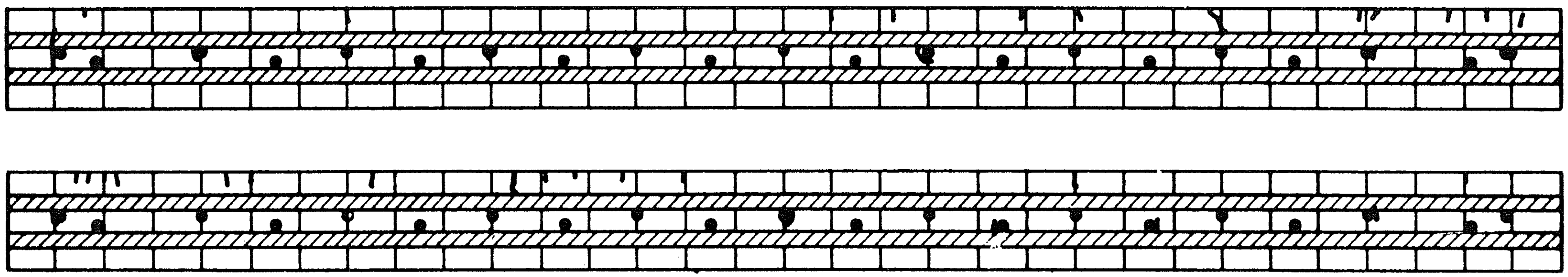


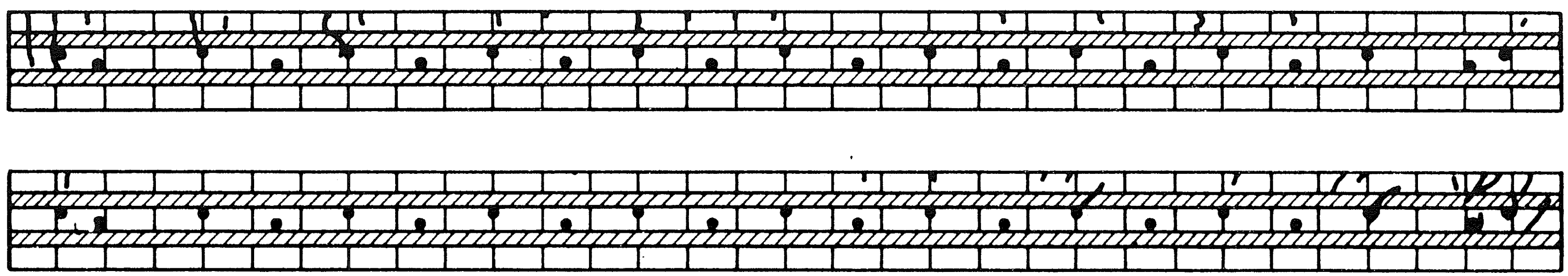
FIG. C 13 INTERNALLY REVIBRATED SLAB — RIGHT HALF OF SLAB FINISHED AFTER REVIBRATION



No Revibration IN-1-SE-0



Spacing of Vibrator Insertion: 24 in. IN-1-SE-20



Spacing of Vibrator Insertion: 12 in. IN-1-SE-80

FIG. C14 SECTIONS OF SEVERELY CRACKED CONCRETE SLABS- INTERNAL REVIBRATION AT LOW OR HIGH ENERGY LEVEL 4 HOURS AFTER MIXING

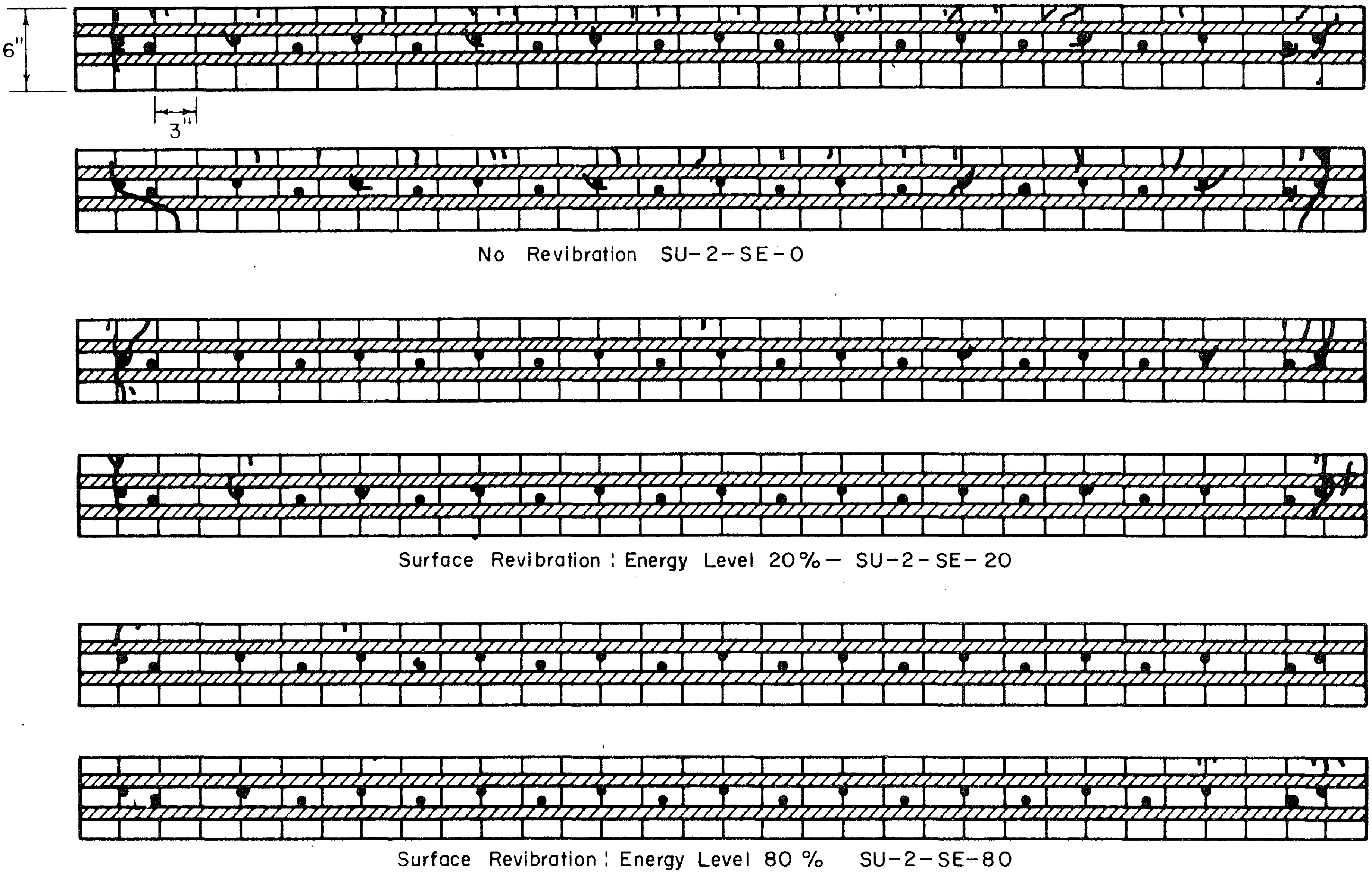


FIG. C15 SECTIONS OF SEVERELY CRACKED CONCRETE SLABS - SURFACE REVIBRATION 4 HOURS AFTER MIXING — ENERGY LEVEL : 20 or 80 %

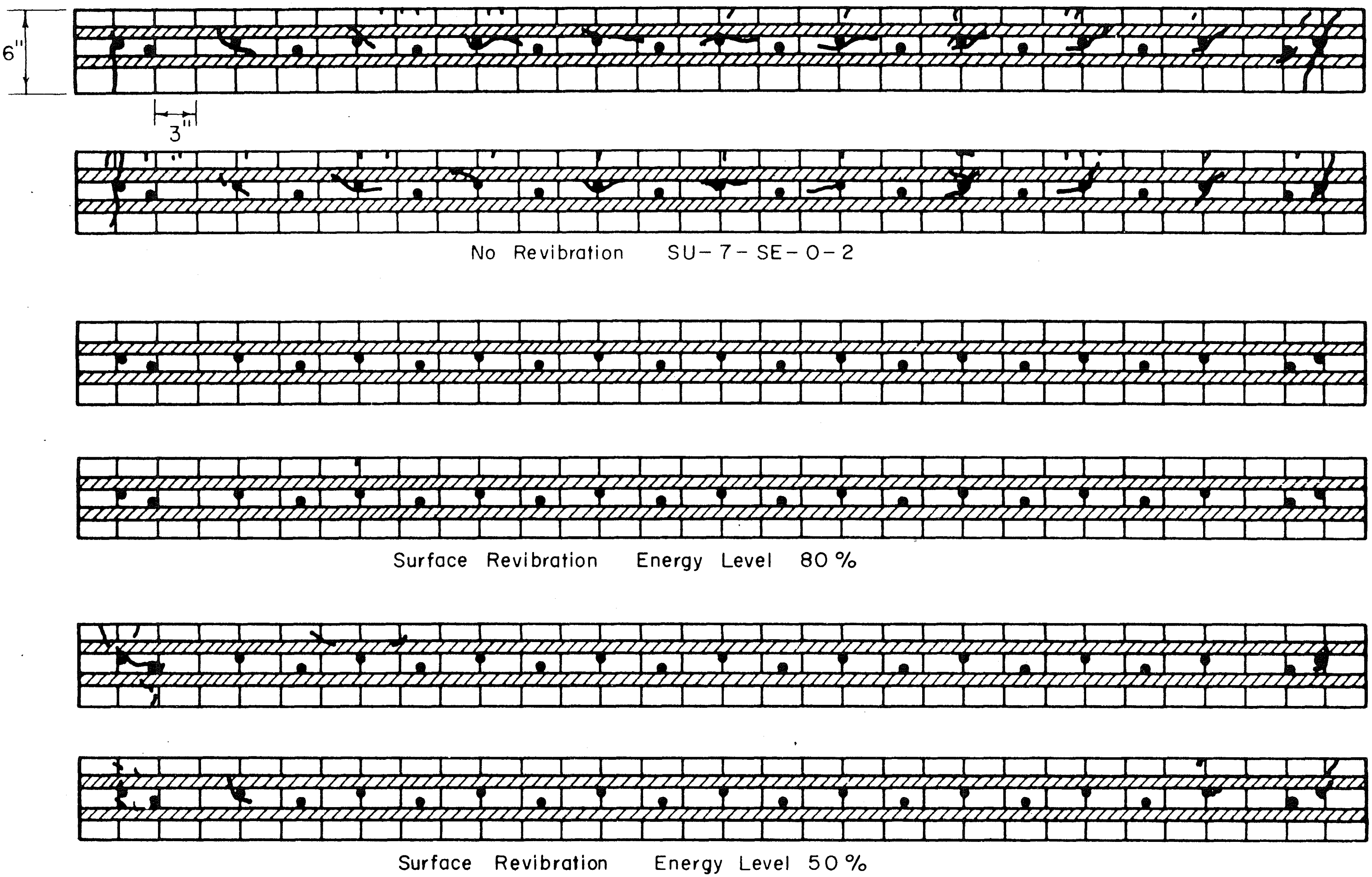


FIG. C16 SECTIONS OF CONCRETE SLABS WITH HORIZONTAL CRACKS; SURFACE REVIBRATION 4 HOURS AFTER MIXING — ENERGY LEVEL; 50 % or 80 %

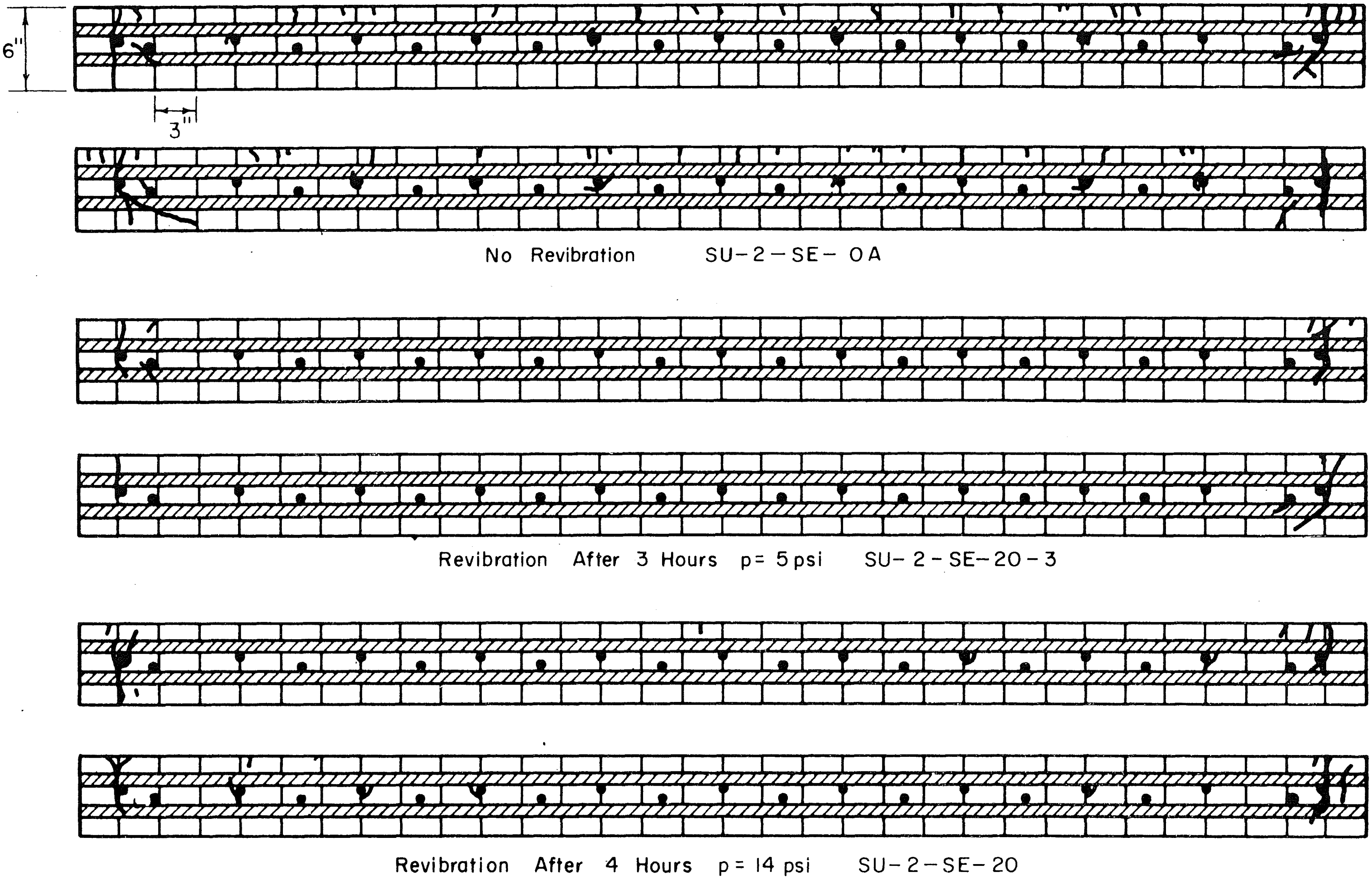
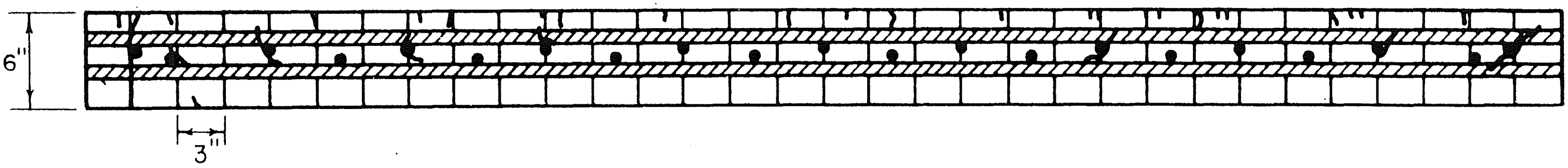
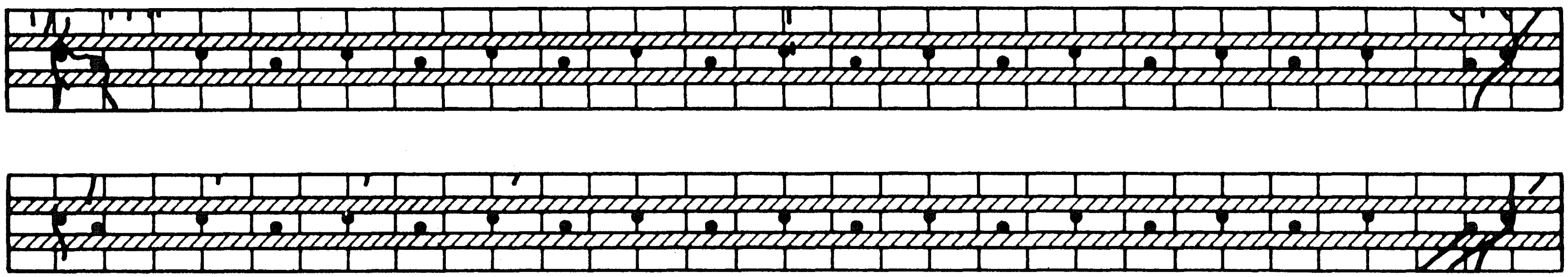


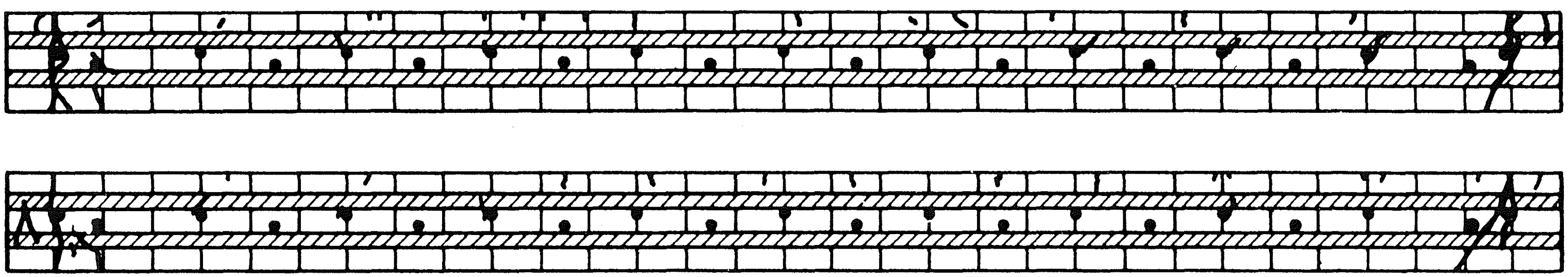
FIG. C17a INFLUENCE OF CONCRETE AGE ON EFFECTIVENESS OF SURFACE REVIBRATION - RETARDED CONCRETE - ENERGY LEVEL: 20 %



No Revibration SU-2-SE-06



Revibration After 5 Hours p= 20 psi SU-2-SE-20-5



Revibration After 7 Hours p= 134 psi SU-2-SE-20-7

FIG. C17b INFLUENCE OF CONCRETE AGE ON EFFECTIVENESS OF SURFACE REVIBRATION – RETARDED CONCRETE – ENERGY LEVEL: 20 %

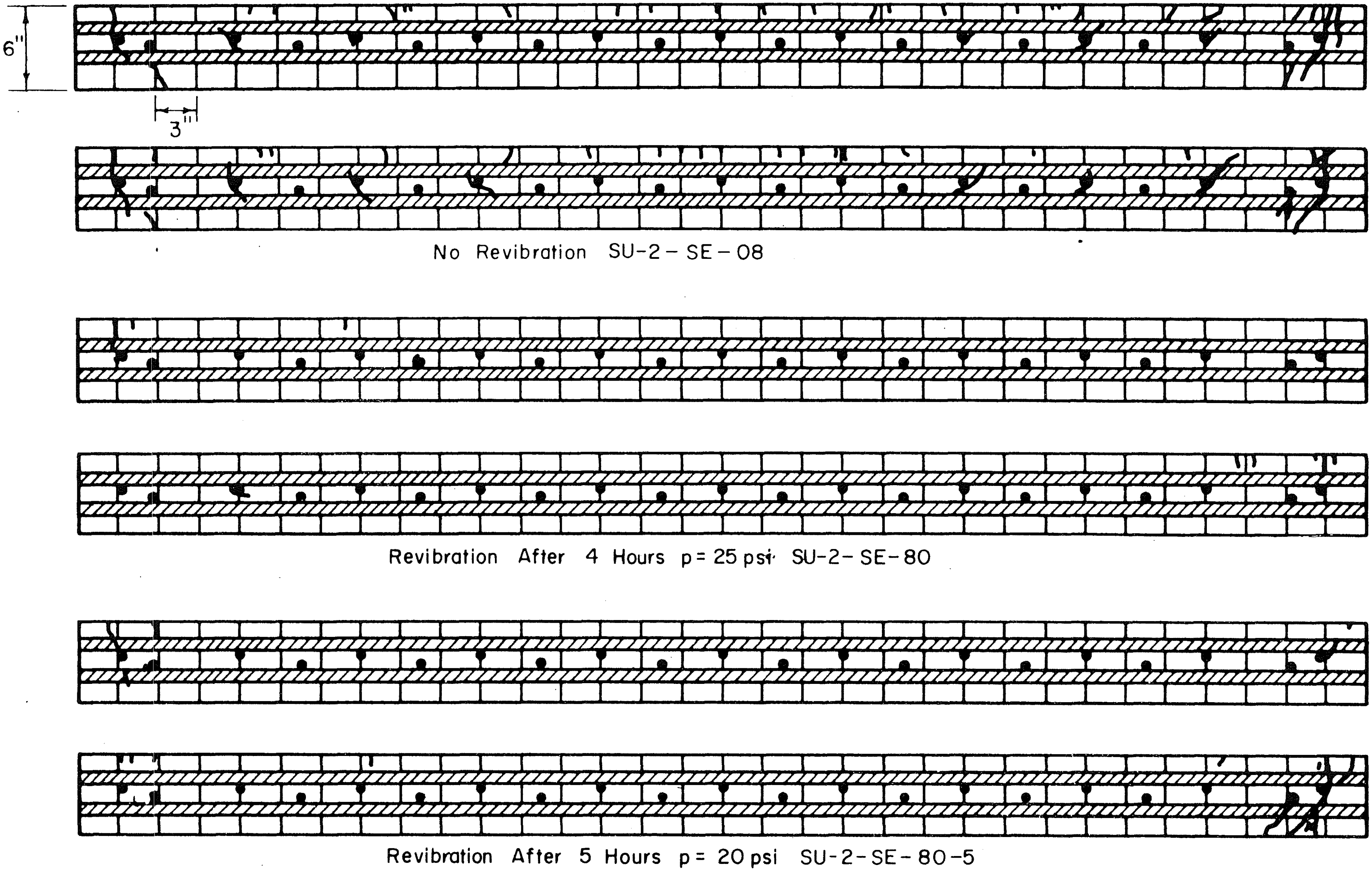
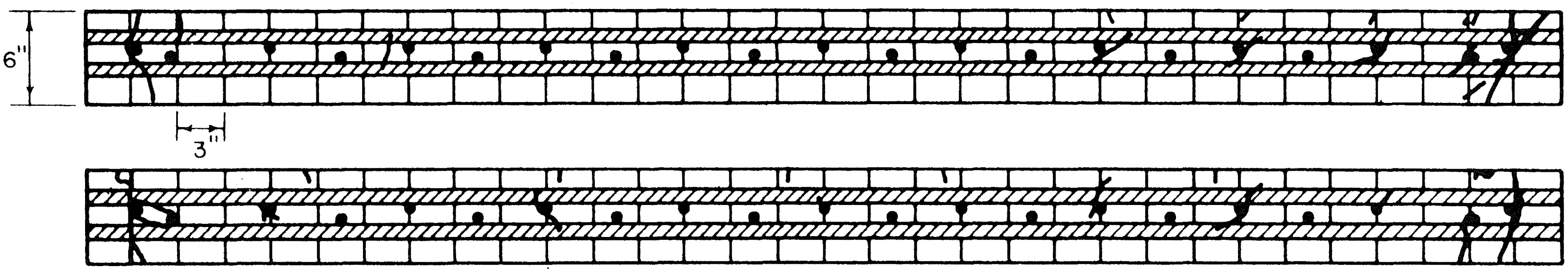


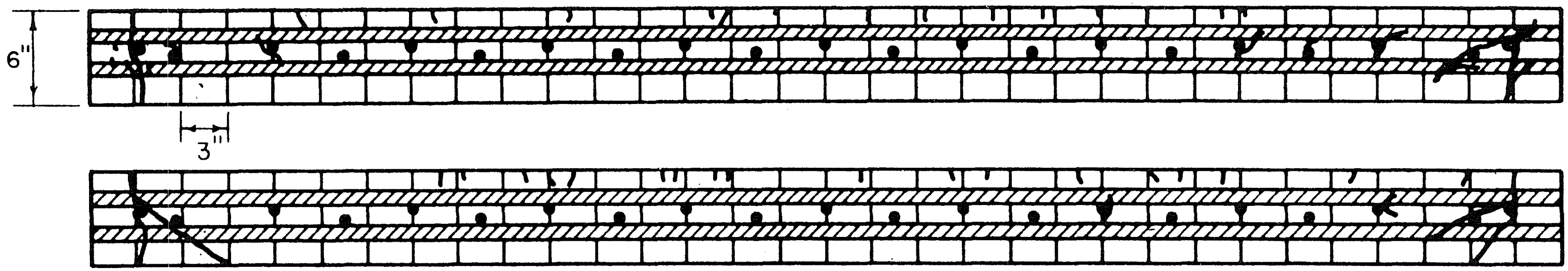
FIG. C18a INFLUENCE OF CONCRETE AGE ON EFFECTIVENESS OF SURFACE REVIBRATION. ENERGY LEVEL: 80% - RETARDED CONCRETE



Revibration After 7 Hours p= 100psi SU-2-SE-80-7

Revibration After 8-1/2 Hours p= 820 psi SU-2-SE-80-8:30

FIG. C18b INFLUENCE OF CONCRETE AGE ON EFFECTIVENESS OF SURFACE REVIBRATION - ENERGY LEVEL : 80% - RETARDED CONCRETE

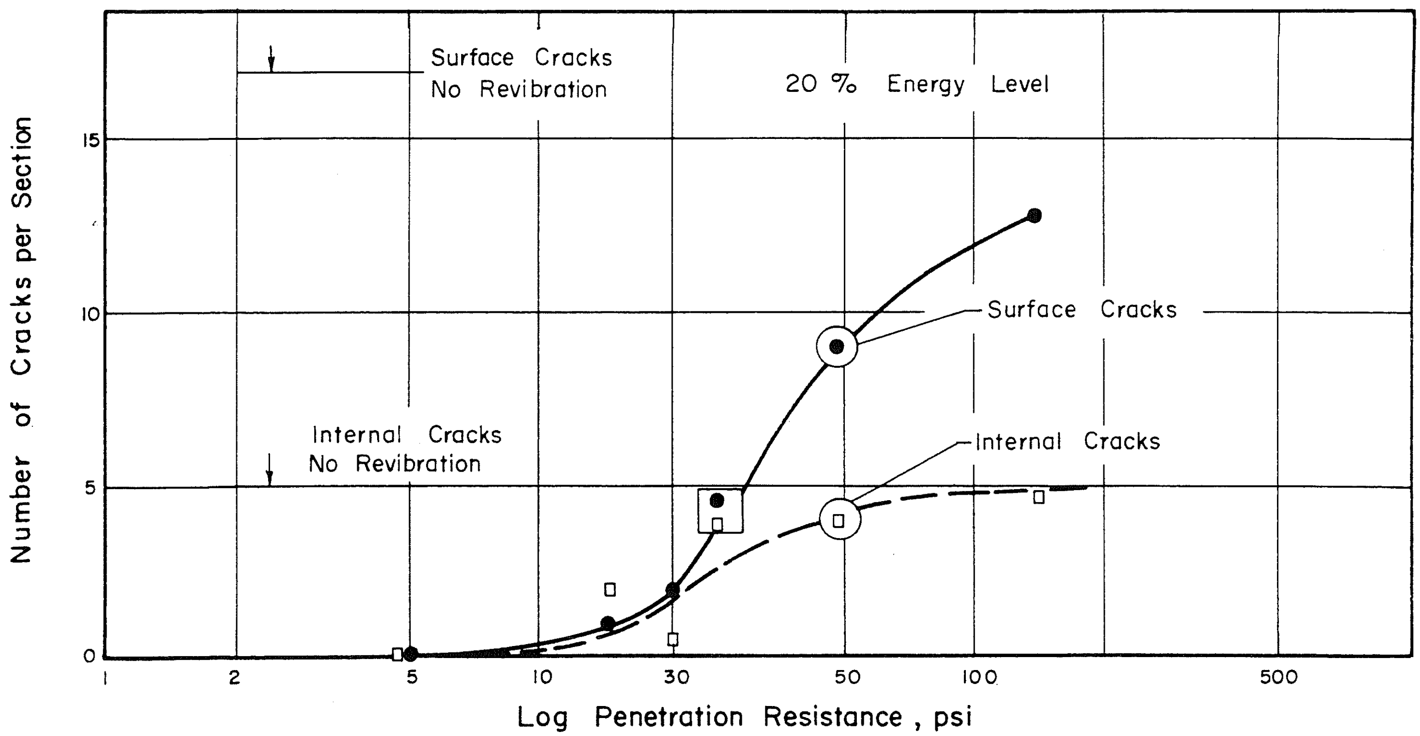


No Revibration SU-4-SE-0

20 % Revibration p = 45 psi SU-4-SE-20

80 % Revibration p = 110 psi SU-4-SE-80

FIG. C19 EFFECTIVENESS OF SURFACE REVIBRATION IN CLOSING CRACKS IN NON-RETARDED CONCRETE - ENERGY LEVEL 20 AND 80% - TIME OF REVIBRATION : 3 HOURS AFTER MIXING



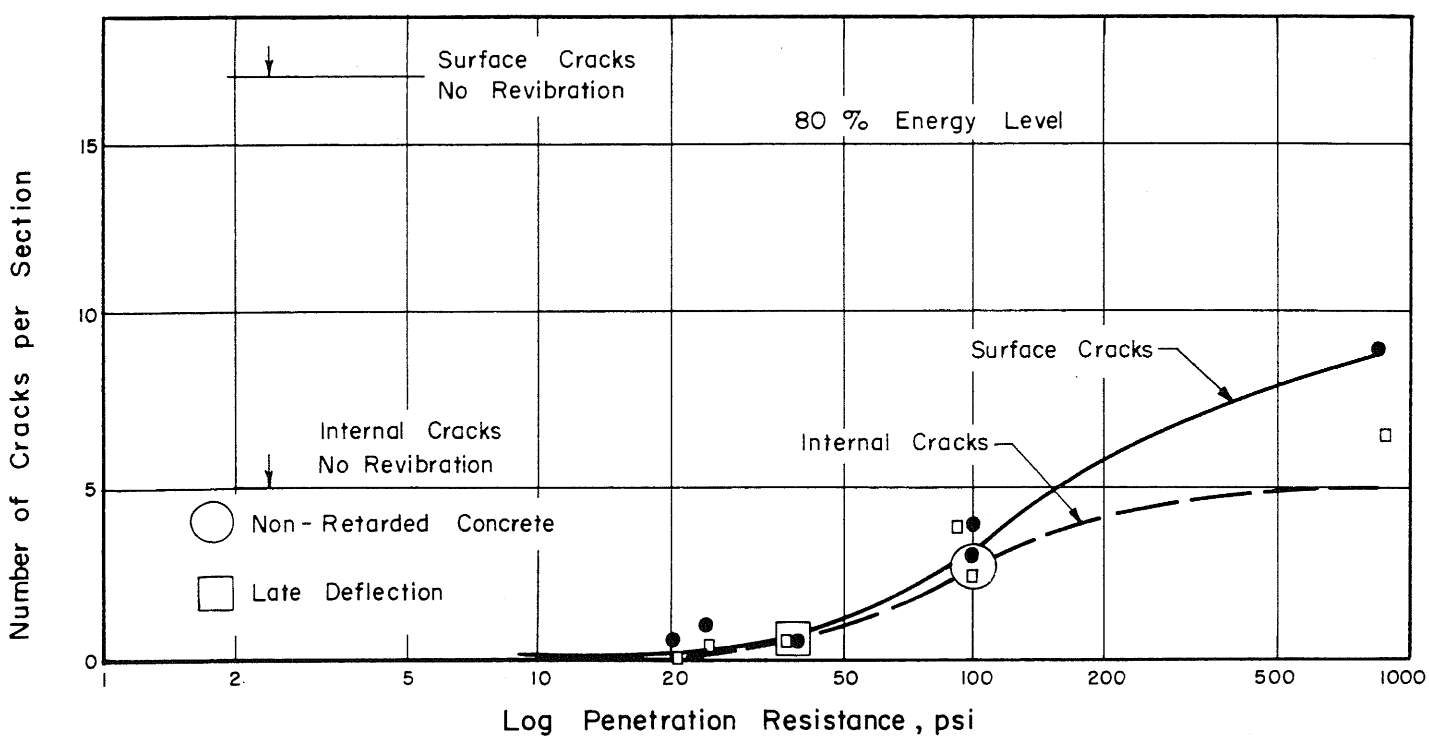
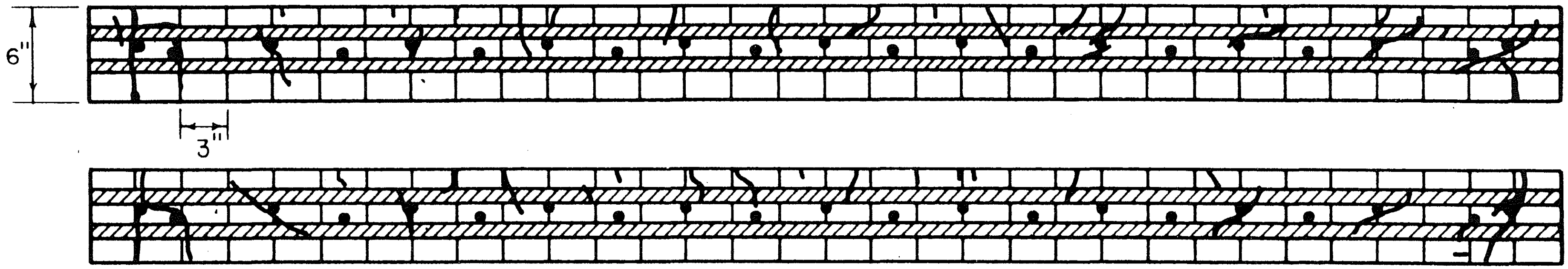
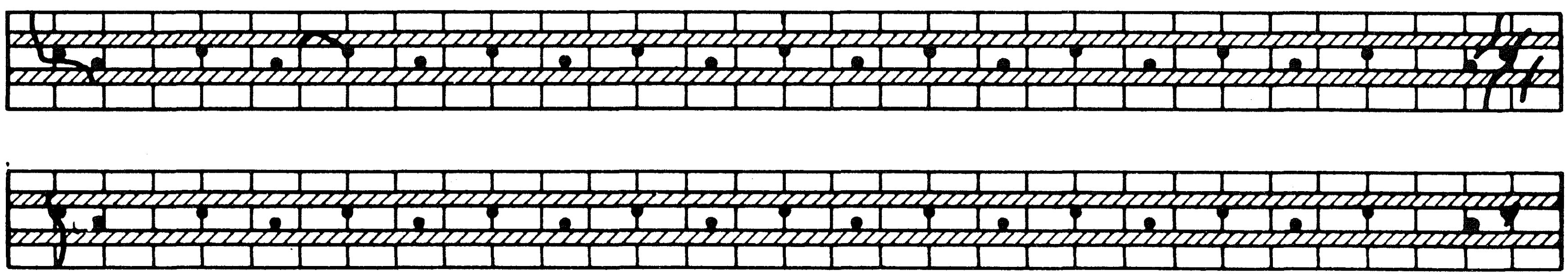


FIG. C20 INFLUENCE OF AGE OF CONCRETE ON EFFECTIVENESS OF SURFACE REVIBRATION; RESULTS FROM SERIES 2; 4 AND 8 SEVERE INITIAL CRACKING



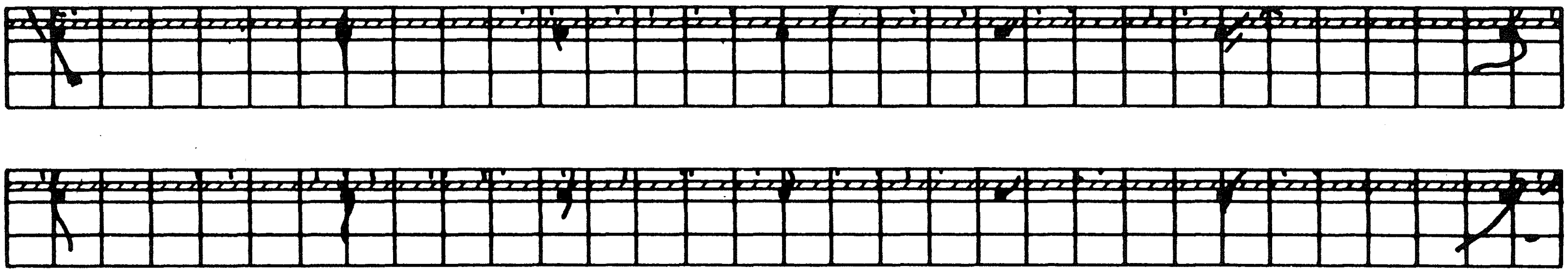
No Revibration SU-8-SE-0

20 % Revibration p=25 psi SU-8-SE-20

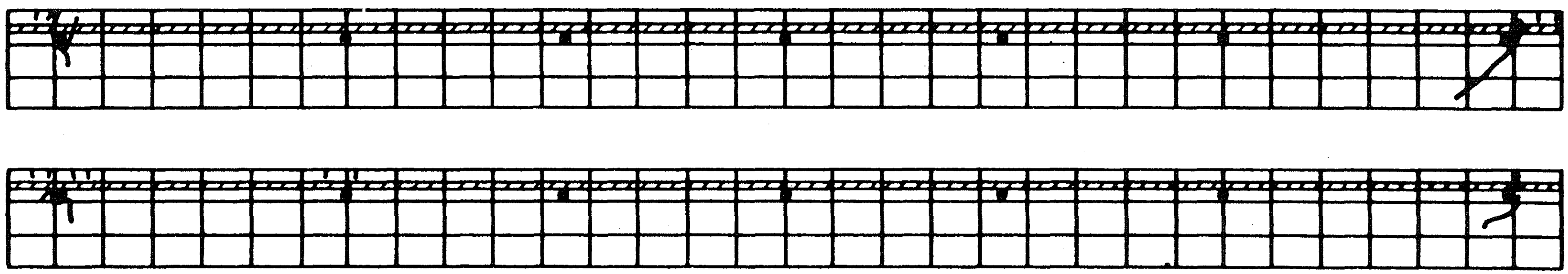


80 % Revibration p=40 psi SU-8-SE-80

FIG. C21 EFFECTIVENESS OF REVIBRATION IN CLOSING CRACKS WHICH WERE FORMED 4-1/2 HOURS AFTER MIXING — TIME OF REVIBRATION: 5 HOURS



No Revibration SU-3L-SE-0



Surface Revibration Energy Level 80 % SU-3L-SE-80

FIG. C22a INFLUENCE OF TOP REINFORCEMENT ON EFFECTIVENESS OF SURFACE REVIBRATION — REINFORCEMENT : TYPE B — CONCRETE COVER : 1 IN. — TIME OF REVIBRATION : 4 HOURS AFTER MIXING

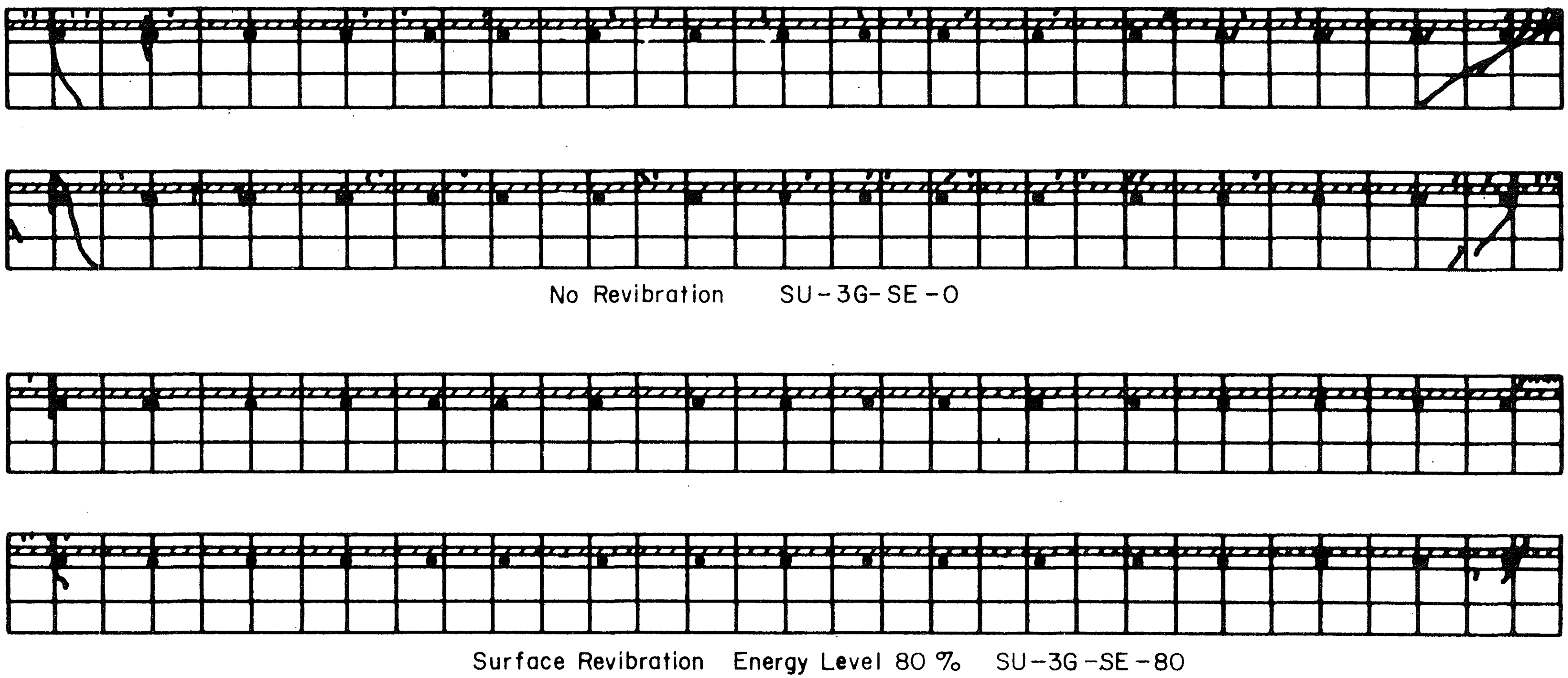
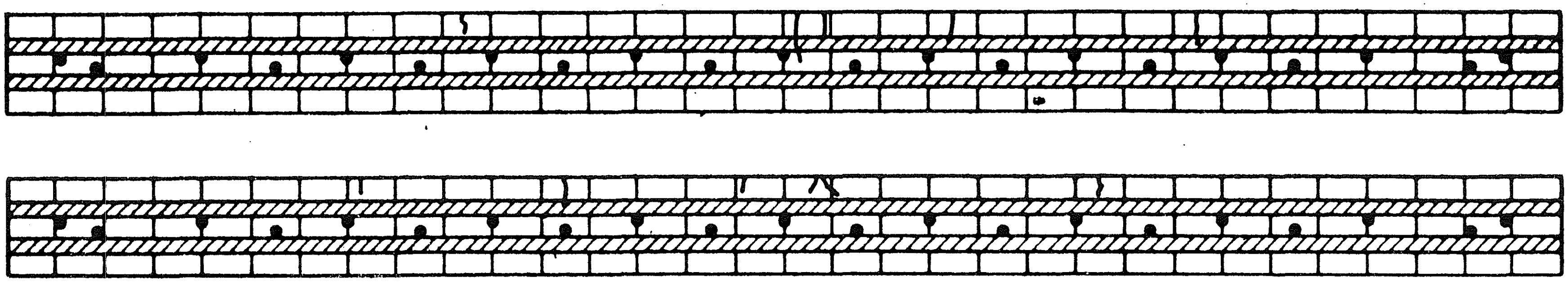


FIG. 22b INFLUENCE OF TOP REINFORCEMENT ON EFFECTIVENESS OF SURFACE REVIBRATION — REINFORCEMENT: TYPE C — CONCRETE COVER: 1 IN. — TIME OF REVIBRATION: 4 HOURS AFTER MIXING

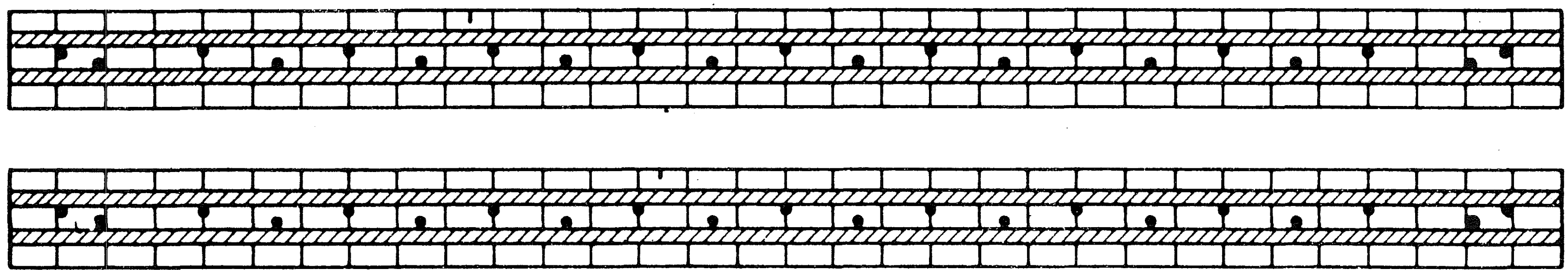
No Revibration SU-5-Nϕ-OA

Surface Revibration Energy Level 80 % SU-5-Nϕ-80

FIG. C23a EFFECTIVENESS OF SURFACE REVIBRATION IN CLOSING EARLY SHRINKAGE CRACKS DUE TO SEVERE EXPOSURE CONDITIONS – CONCRETE SURFACE TEMPERATURE : 110°F DURATION OF HEATING : 45 MINUTES



No Revibration SU-5-Nϕ-OB



Surface Revibration Energy Level 80 % SU-5-Nϕ-80B

FIG. C23b EFFECTIVENESS OF SURFACE REVIBRATION IN CLOSING EARLY SHRINKAGE CRACKS DUE TO SEVERE EXPOSURE CONDITIONS – CONCRETE SURFACE TEMPERATURE : 95°F DURATION OF HEATING : 1-1/2 HOURS

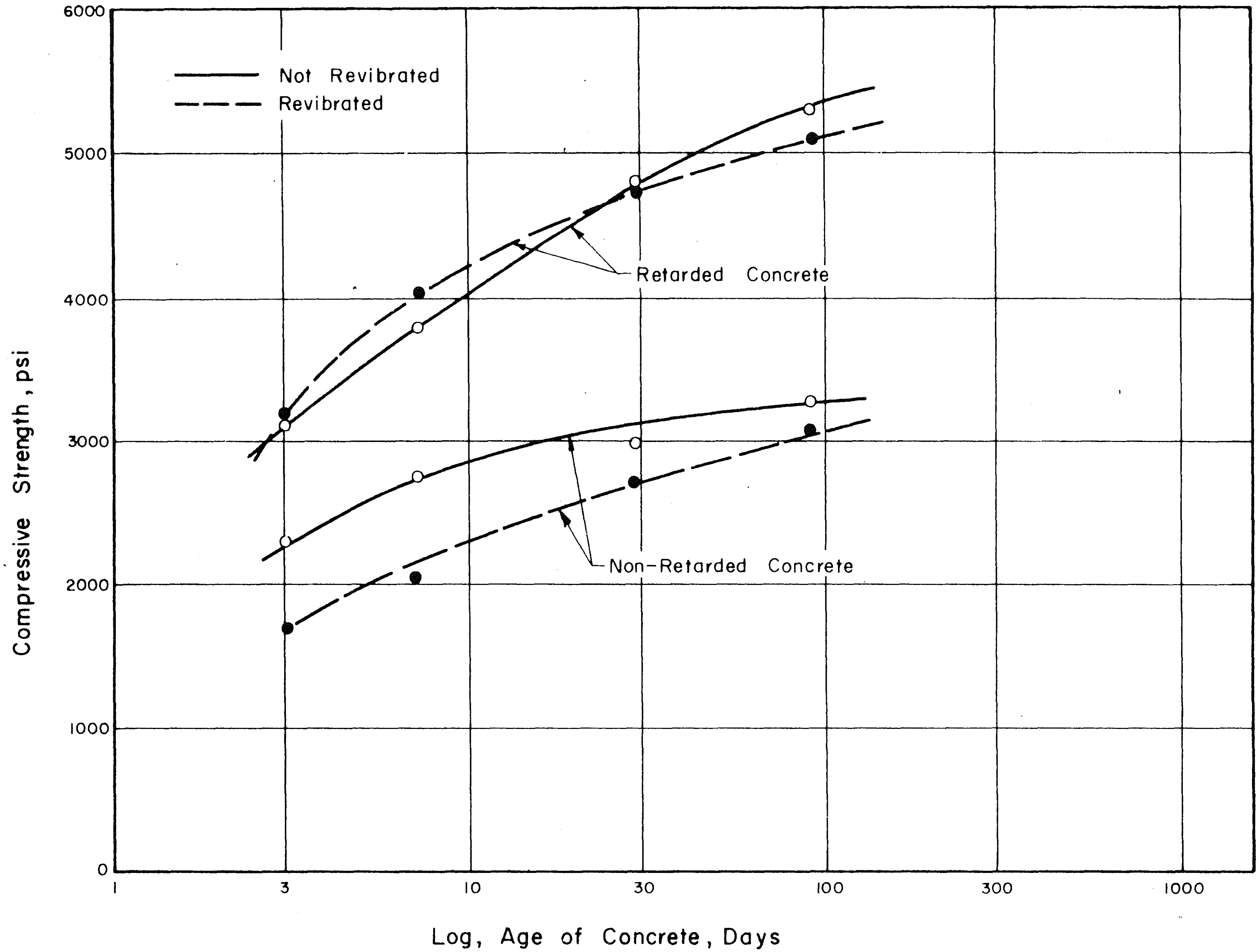


FIG. C24 EFFECT OF REVIBRATION ON COMPRESSIVE STRENGTH OF RETARDED AND NON-RETARDED CONCRETE PRISMS – 6 BY 6 BY 18 in. – REVIBRATED FOR 40 sec. ON A VIBRATING TABLE – TIME OF REVIBRATION: 4 HOURS AFTER MIXING

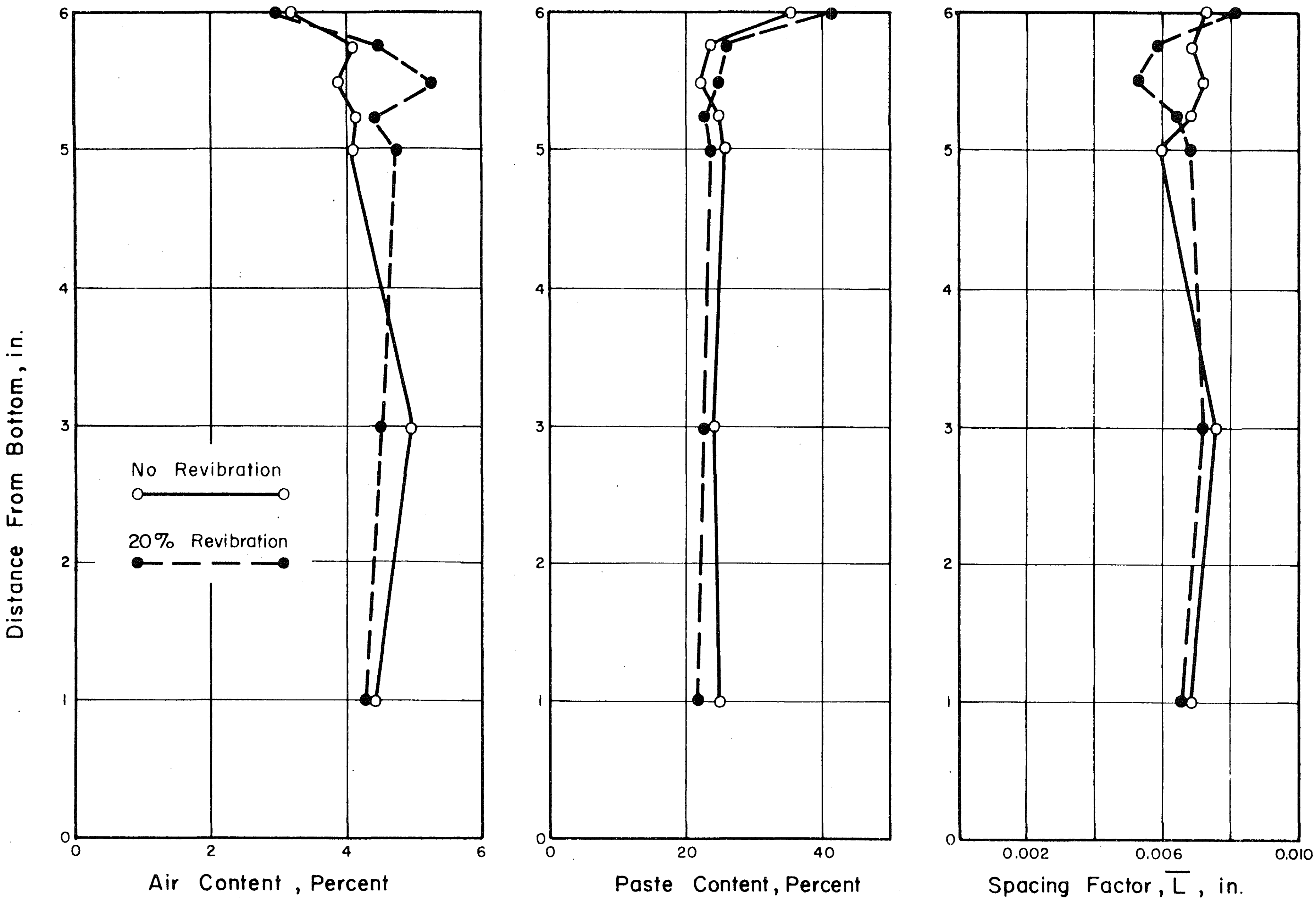


FIG. C25a EFFECT OF SURFACE REVIBRATION ON AIR VOID CHARACTERISTICS OF CONCRETE — ENERGY LEVEL : 20 %

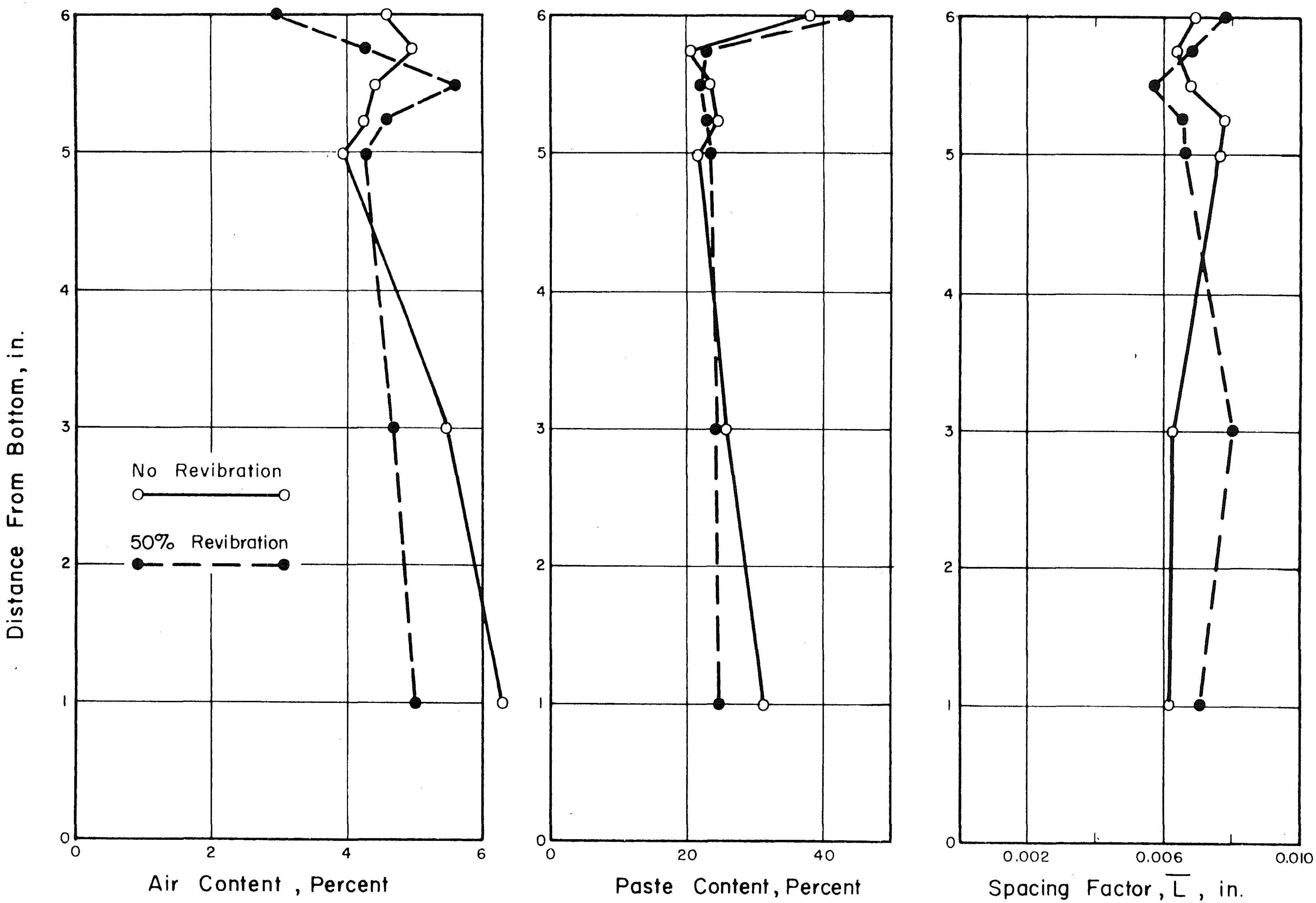


FIG. C25b EFFECT OF SURFACE REVIBRATION ON AIR VOID CHARACTERISTICS OF CONCRETE – ENERGY LEVEL: 50 %

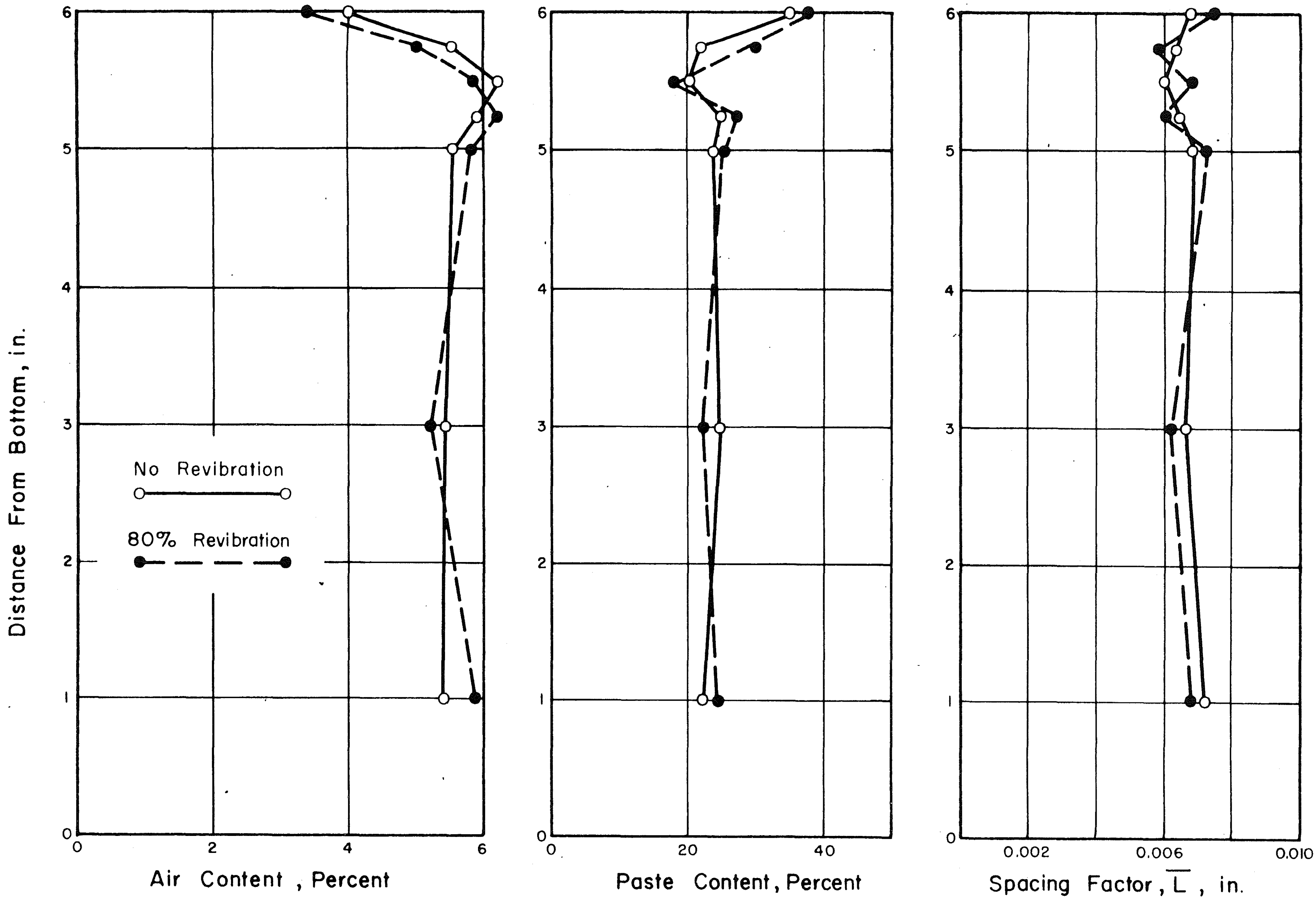


FIG. C25c EFFECT OF SURFACE REVIBRATION ON AIR VOID CHARACTERISTICS OF CONCRETE – ENERGY LEVEL 80 %

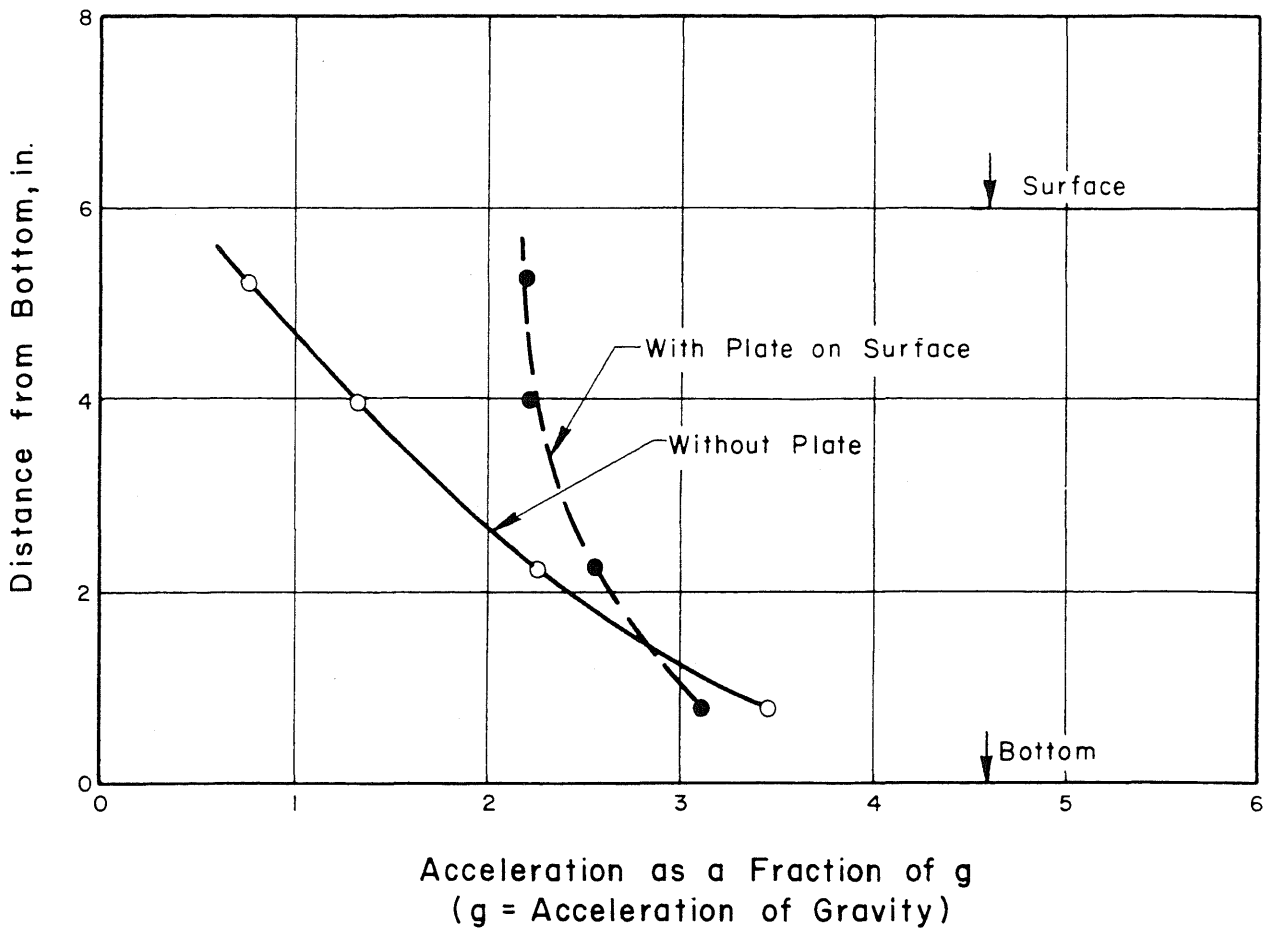


FIG.C26 DISTRIBUTION OF ACCELERATION DURING REVIBRATION — EXTERNAL REVIBRATION OF SPECIMEN 22 in. BY 22 in. BY 6 in.

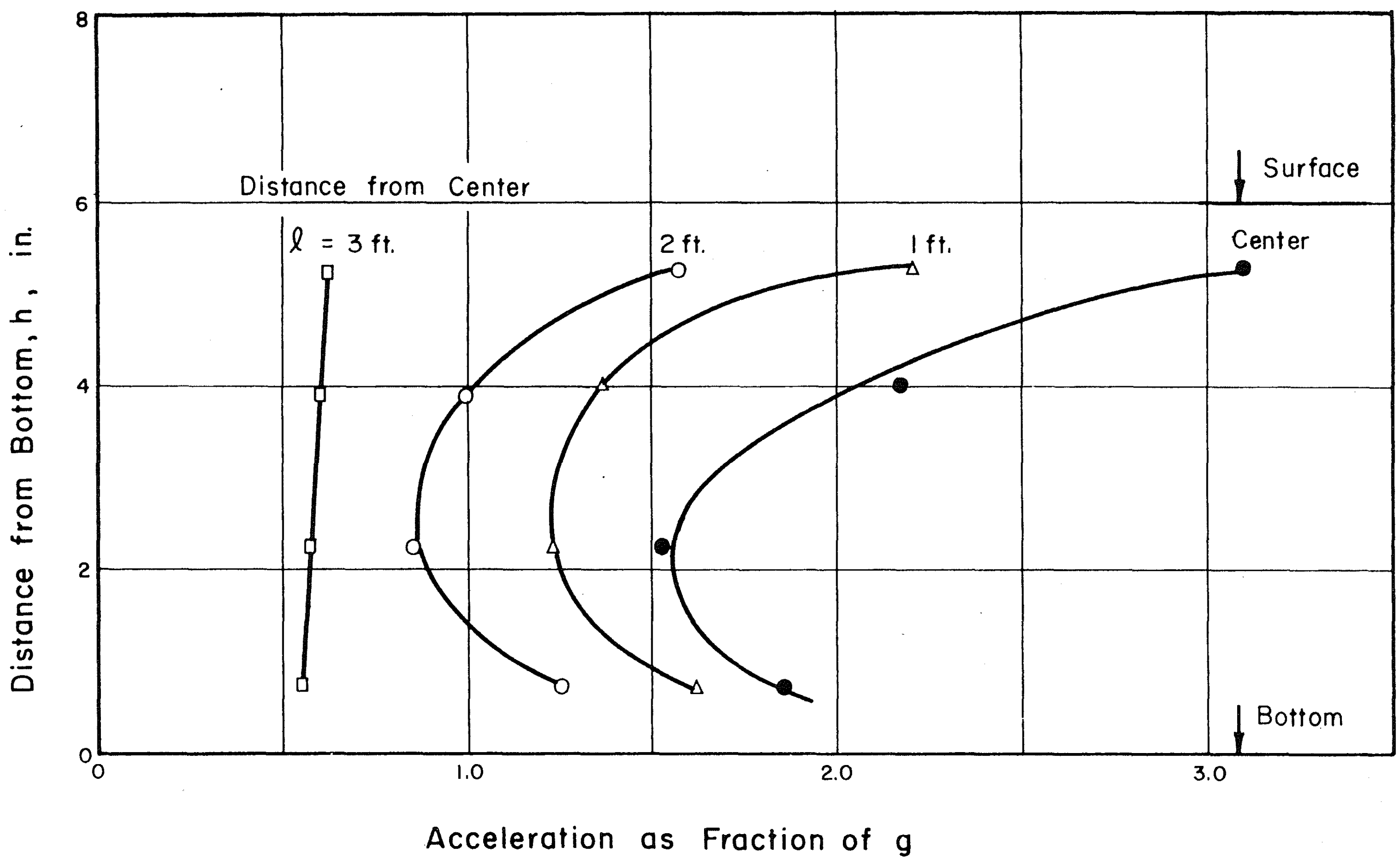


FIG. C27 DISTRIBUTION OF ACCELERATION DURING REVIBRATION — SURFACE REVIBRATION OF SPECIMEN 3 ft BY 8 ft BY 6 in. — ENERGY LEVEL 80 %

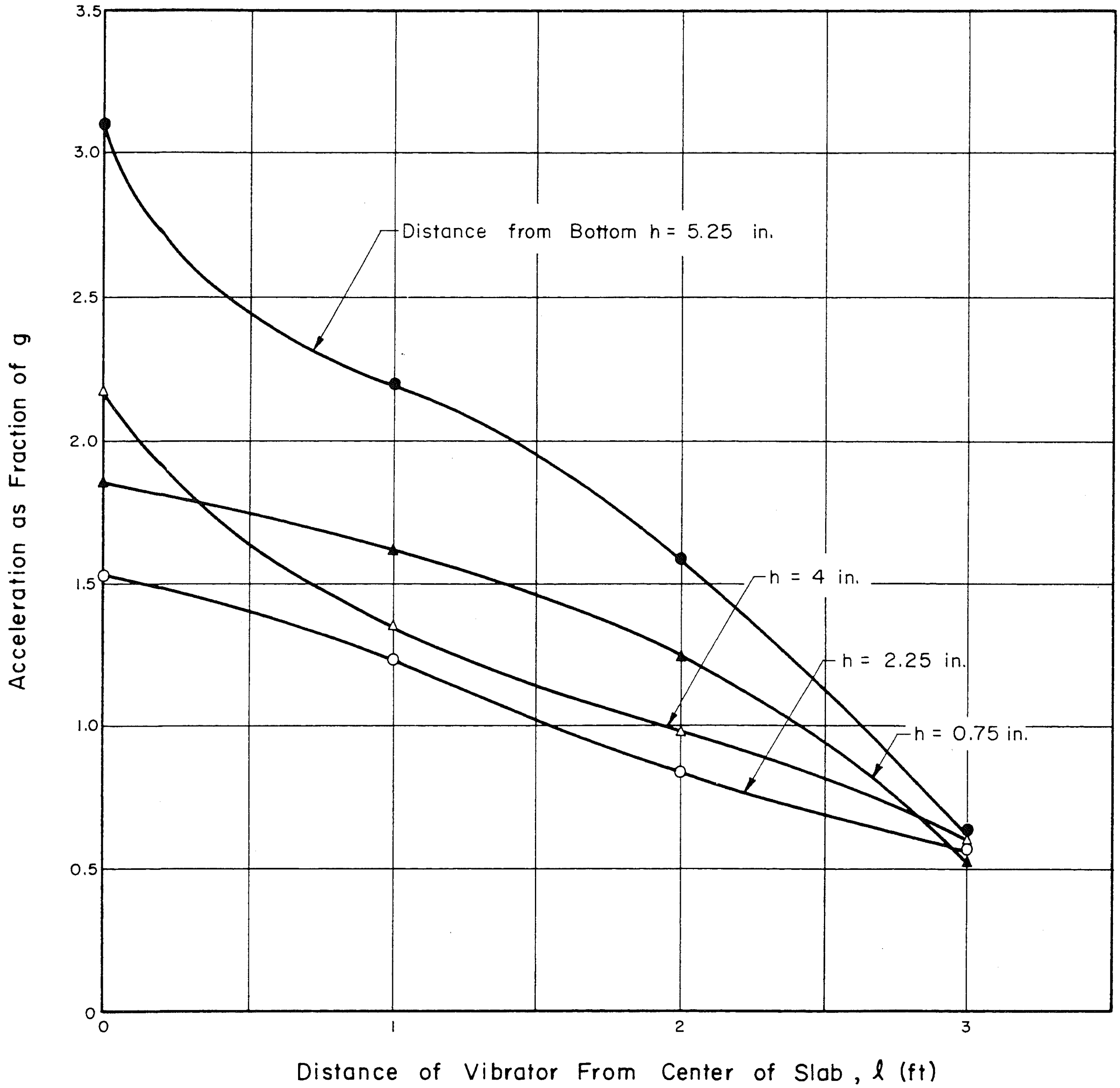


FIG. C 28 ACCELERATION DURING REVIBRATION AS FUNCTION OF POSITION OF THE VIBRATOR - SURFACE REVIBRATION OF SPECIMEN 3 ft BY 8 ft BY 6 in. - ENERGY LEVEL 80 %

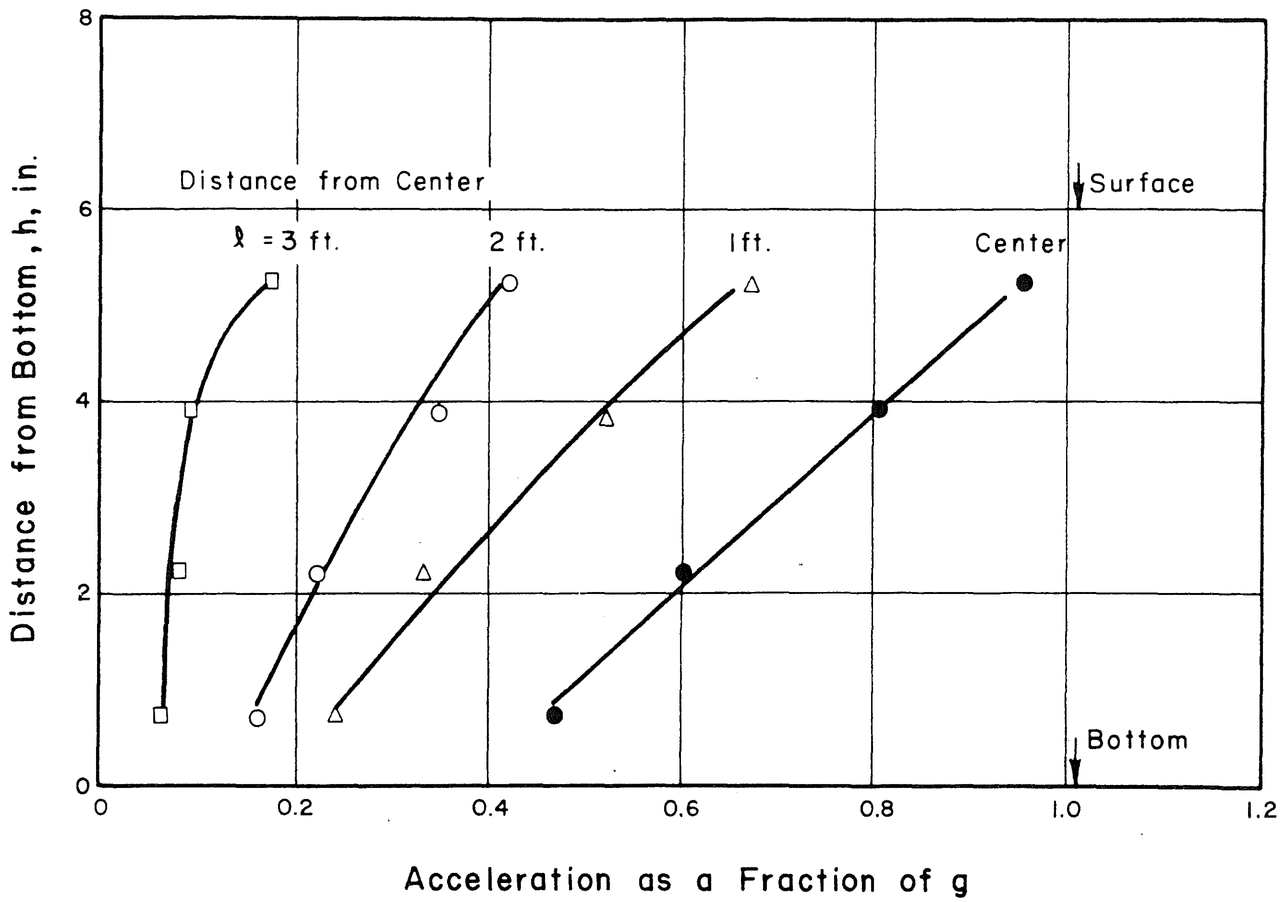


FIG. C29 DISTRIBUTION OF ACCELERATION DURING REVIBRATION — SURFACE REVIBRATION OF SPECIMEN 3 ft BY 8 ft BY 6 in. — ENERGY LEVEL 20 %

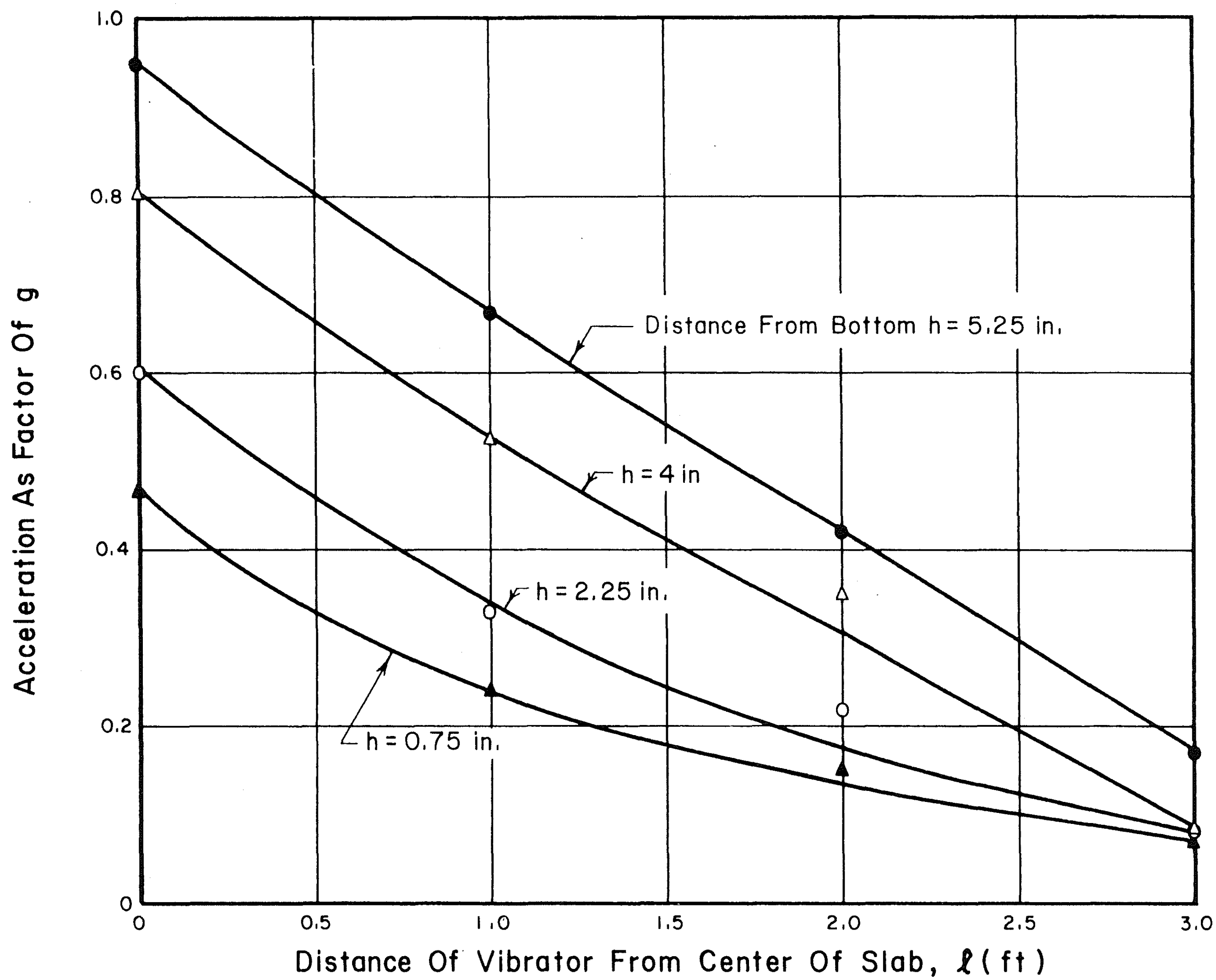


FIG. C30 ACCELERATION DURING REVIBRATION AS FUNCTION OF POSITION OF THE VIBRATOR — SURFACE REVIBRATION OF SPECIMEN 3 ft BY 8 ft BY 6 in. — ENERGY LEVEL 20 %

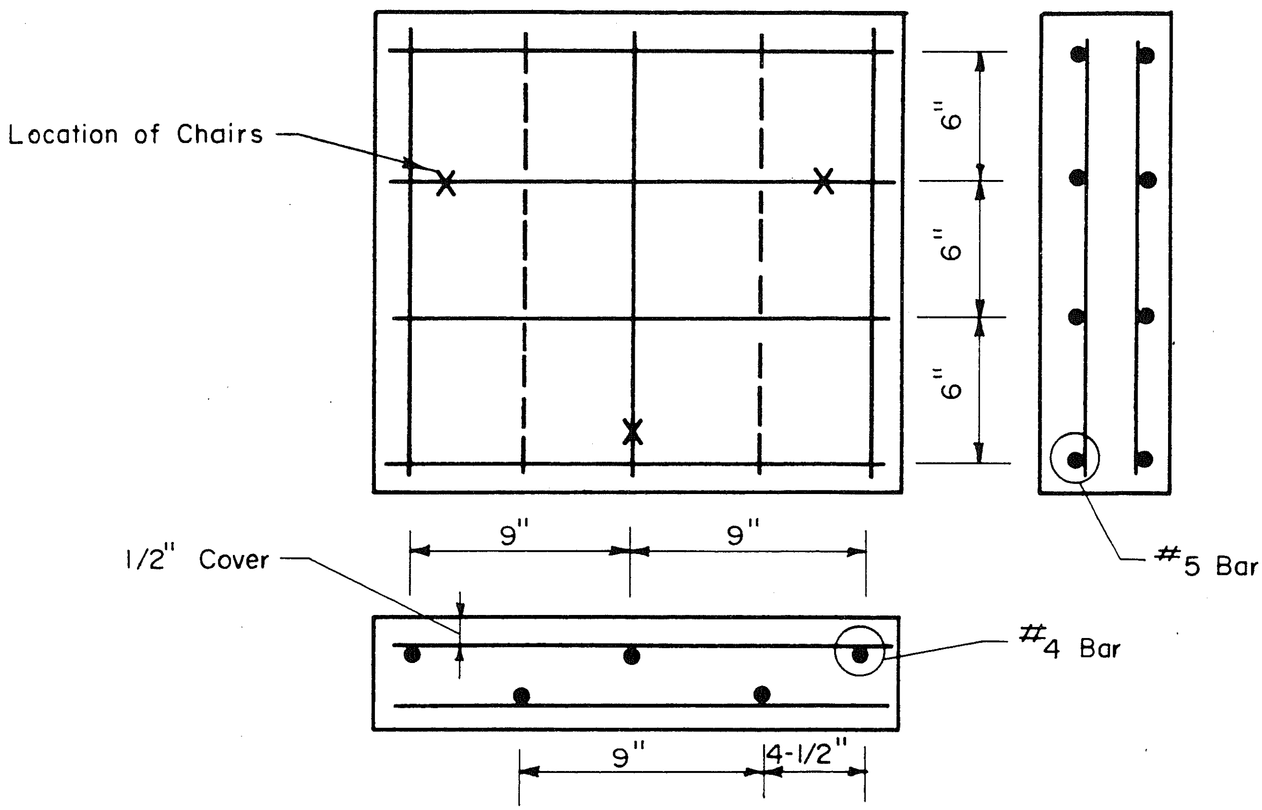


FIG. D31 LAYOUT OF REINFORCEMENT – PHASE 3a

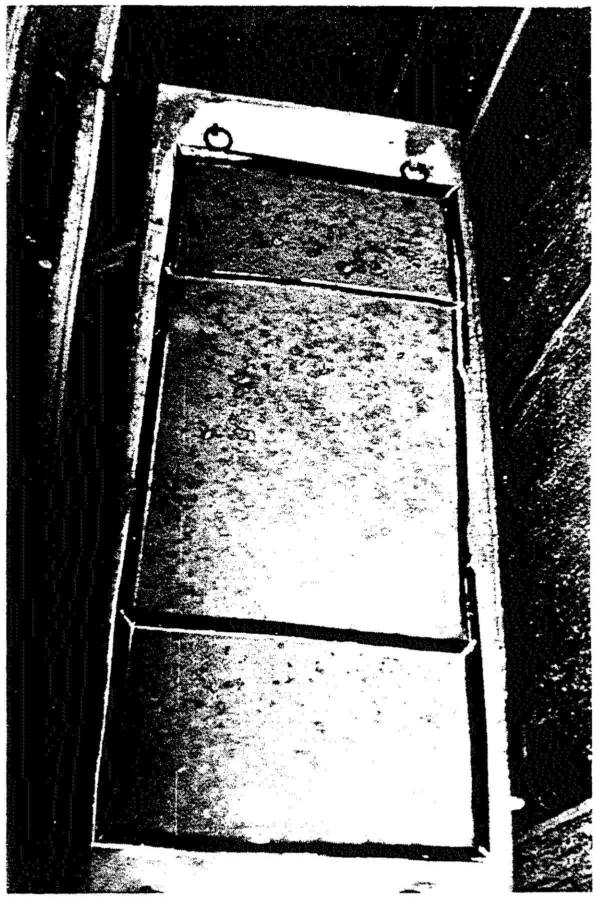


FIG. D32 PONDED SLAB FOR FREEZE-THAW TESTS—PHASE 3b

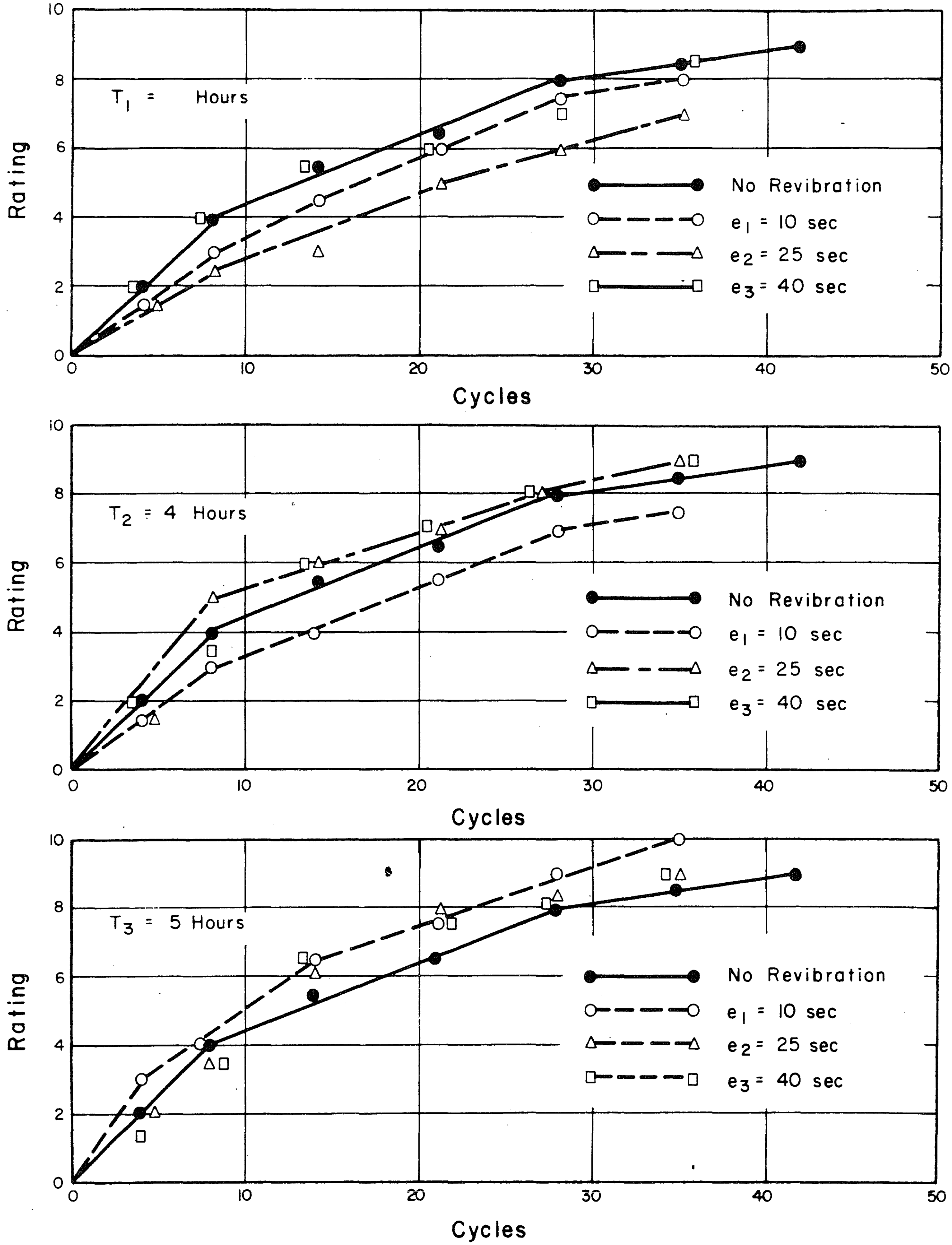


FIG. D33 INFLUENCE OF EXTERNAL REVIBRATION ON SURFACE DETERIORATION OF REINFORCED, RETARDED CONCRETE – AIR CONTENT OF CONCRETE: 5.5 TO 6.5 % – PHASE 3a – SERIES IA

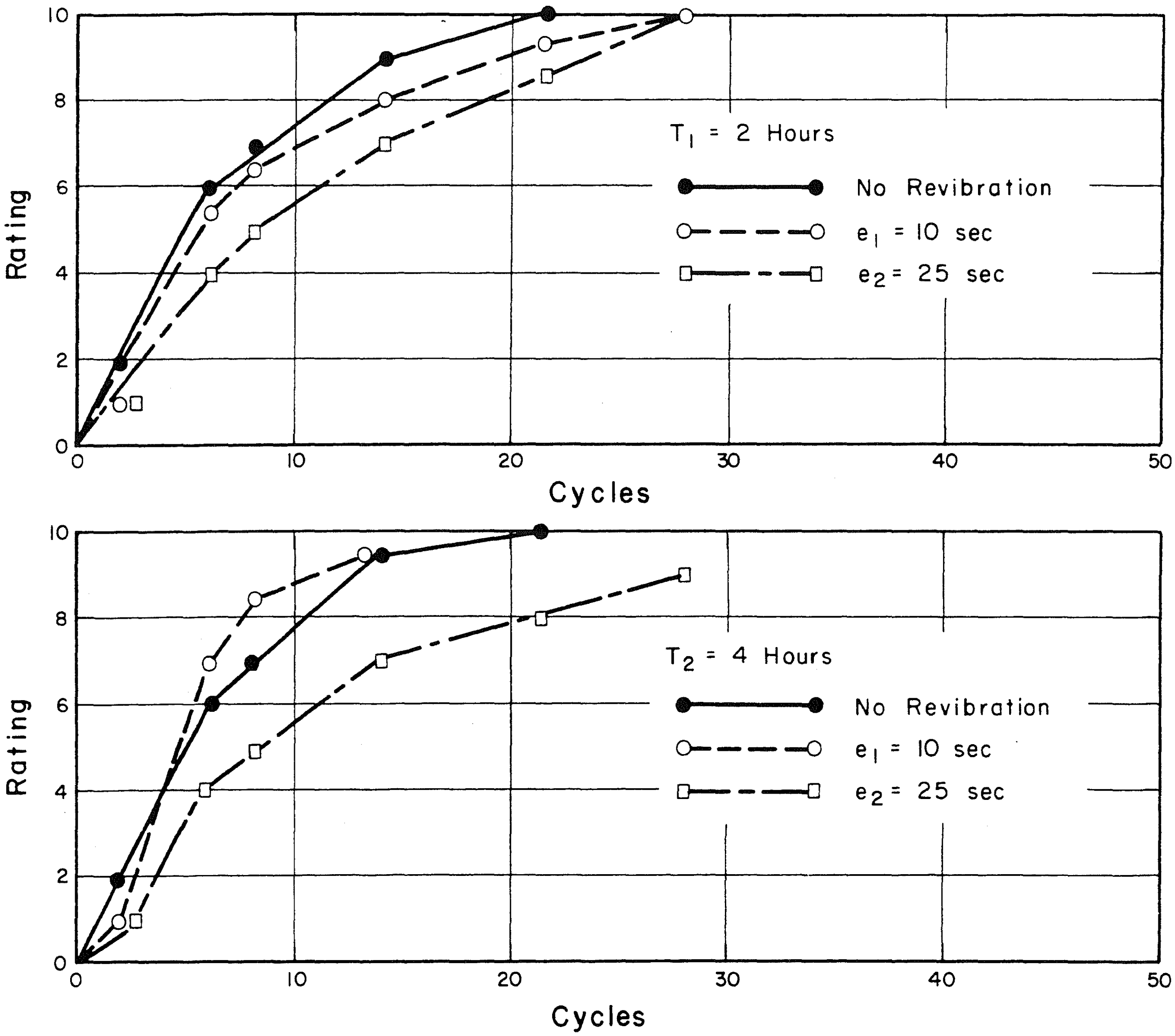


FIG. D34 INFLUENCE OF EXTERNAL REVIBRATION ON SURFACE DETERIORATION OF REINFORCED, RETARDED CONCRETE - AIR CONTENT OF CONCRETE: 4.5 TO 4.9 % - PHASE 3a - SERIES 2A

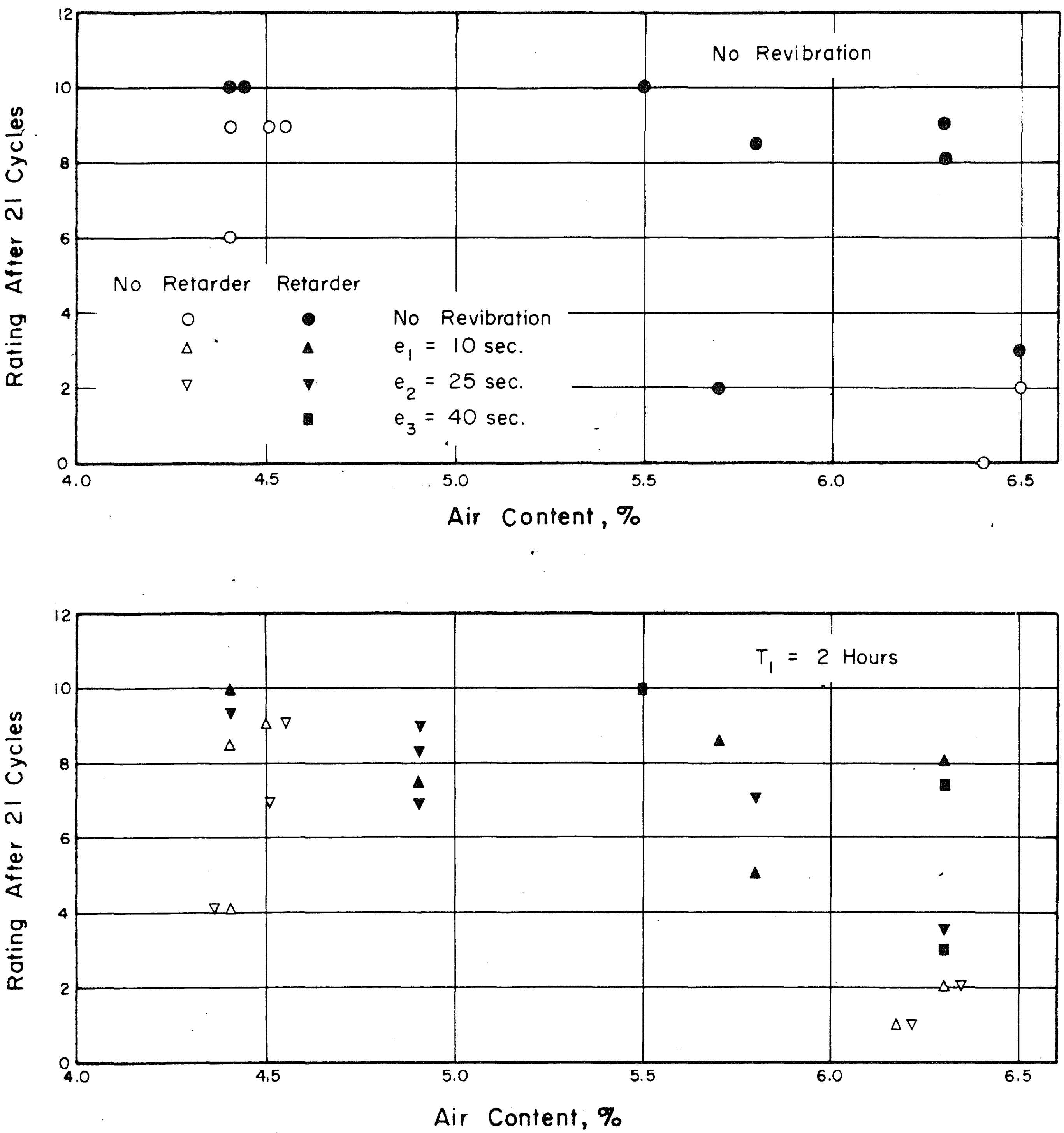


FIG. D35a EFFECT OF AIR CONTENT OF CONCRETE ON SURFACE DETERIORATION AFTER 21 FREEZING AND THAWING CYCLES — RESULTS FROM PHASE 3a - SERIES 1A; 2A; 2B AND 2C

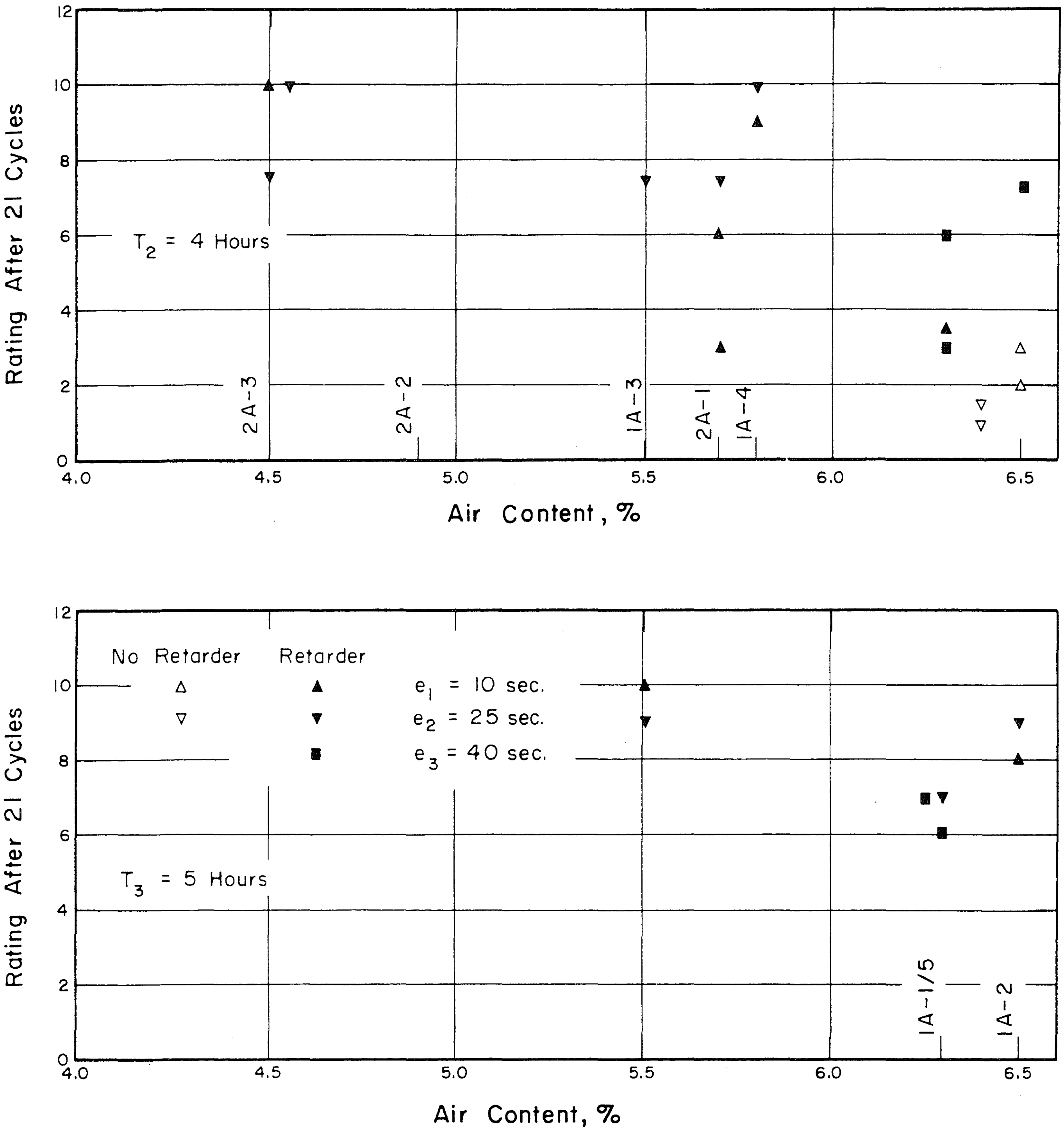


FIG. D35b EFFECT OF AIR CONTENT OF CONCRETE ON SURFACE DETERIORATION AFTER 21 FREEZING AND THAWING CYCLES — RESULTS FROM PHASE 3a - SERIES IA; 2A; 2B AND 2C

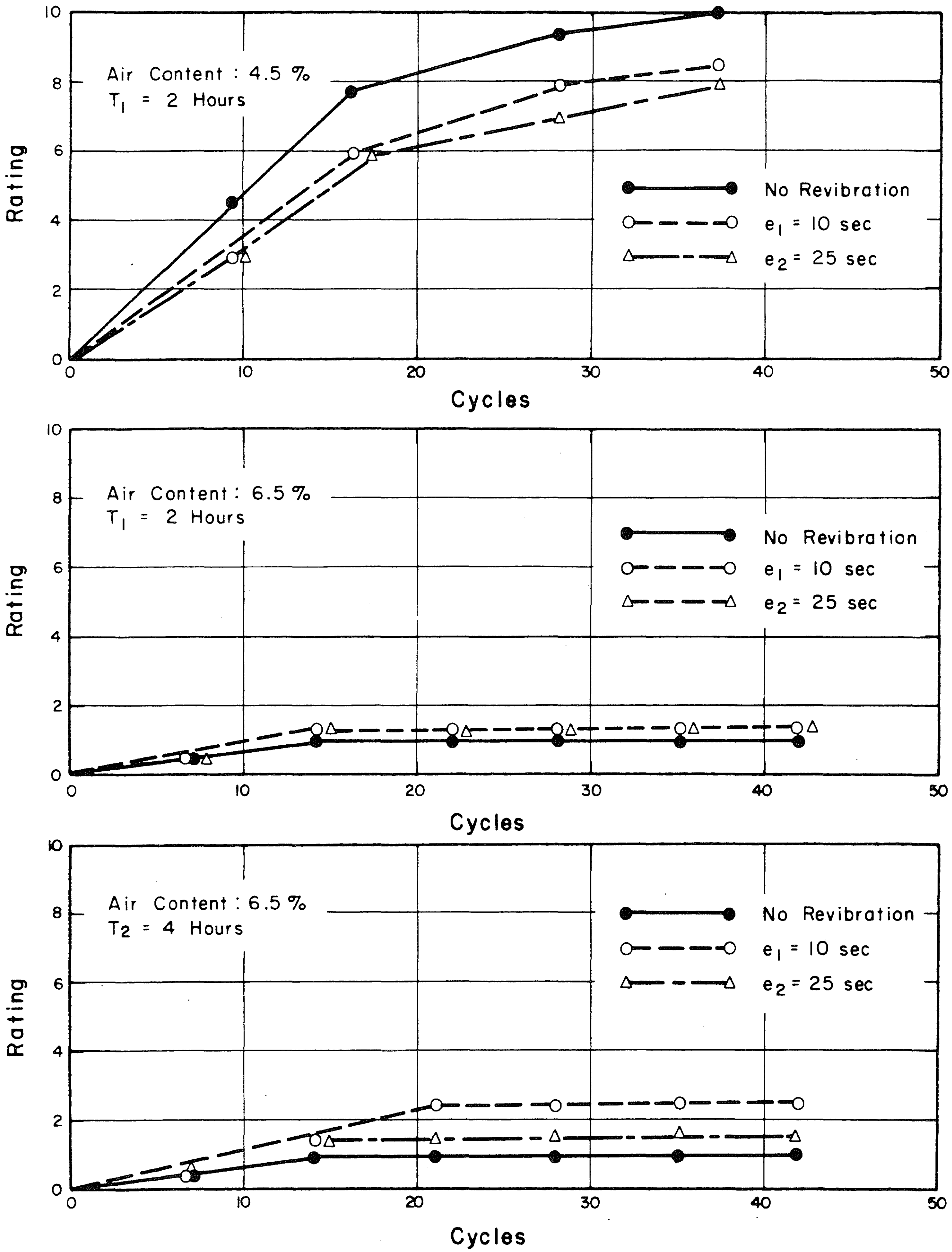


FIG. D36 INFLUENCE OF EXTERNAL REVIBRATION ON SURFACE DETERIORATION OF REINFORCED, NON-RETARDED CONCRETE- PHASE 3a – SERIES 2B AND 2C

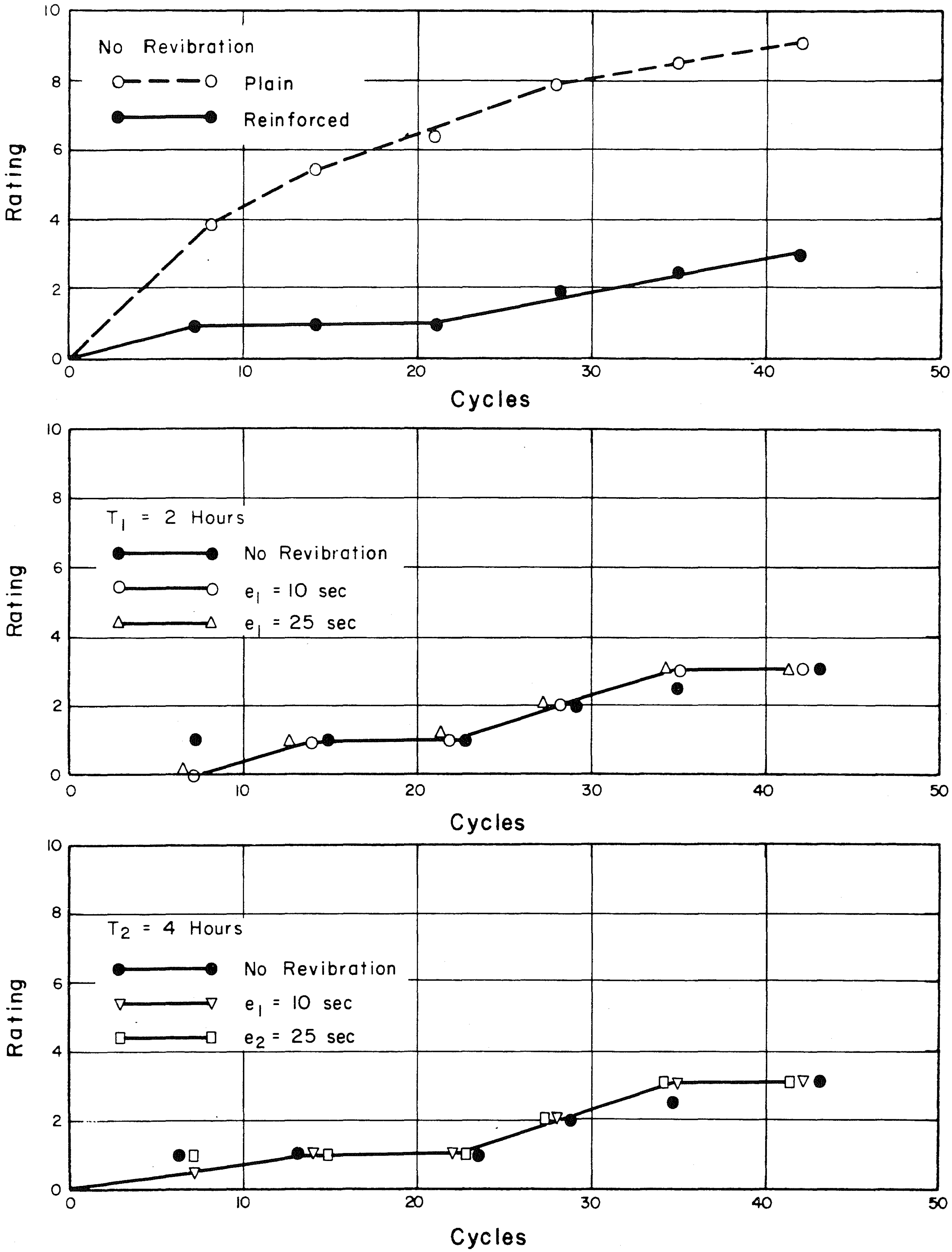
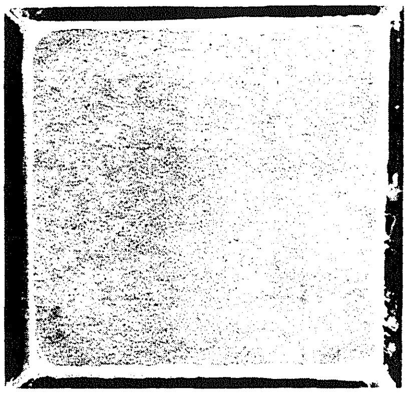
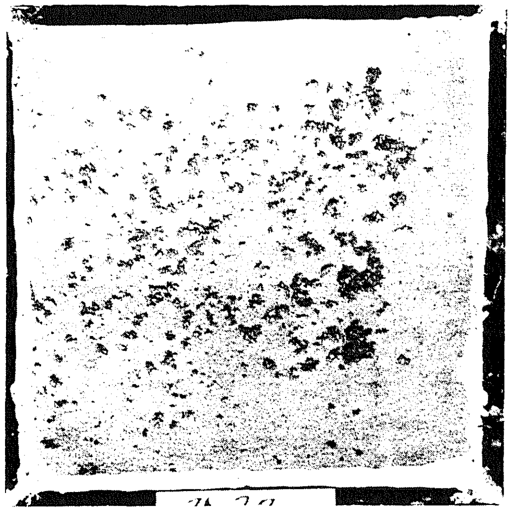


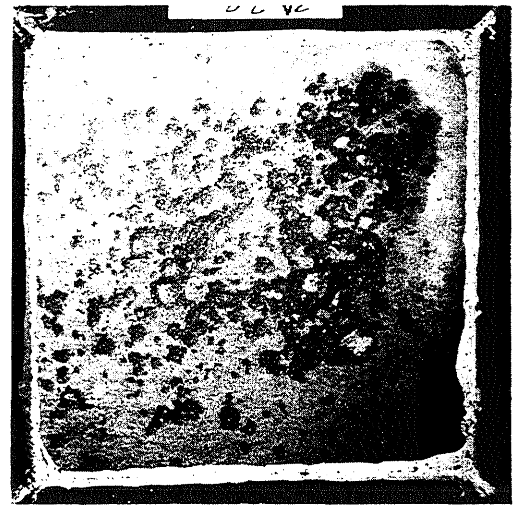
FIG. D37 INFLUENCE OF EXTERNAL REVIBRATION ON SURFACE DETERIORATION OF UNREINFORCED, RETARDED CONCRETE — PHASE 3a — SERIES 3



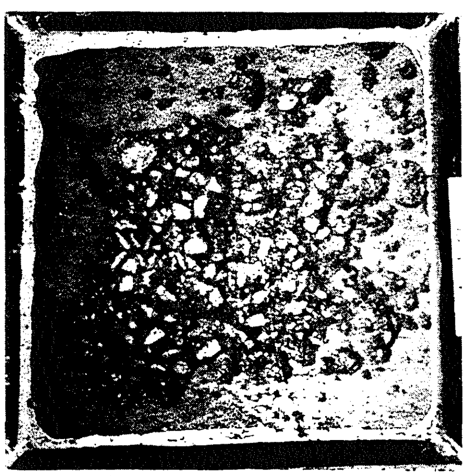
Cycles : 0
Rating : 0



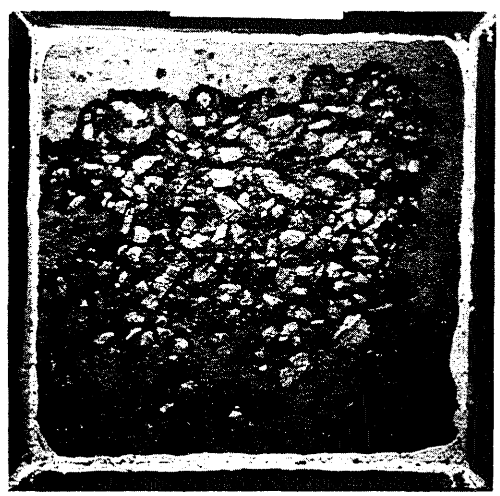
Cycles : 9
Rating : 2



Cycles : 16
Rating : 4



Cycles : 28
Rating : 7



Cycles : 37
Rating : 9

FIG. D38 SURFACE DETERIORATION OF SPECIMEN 2A-2-2
PHASE 3a — SERIES 2A ; EXTERNAL REVIBRATION
T = 4 HOURS ; e = 25 SECONDS

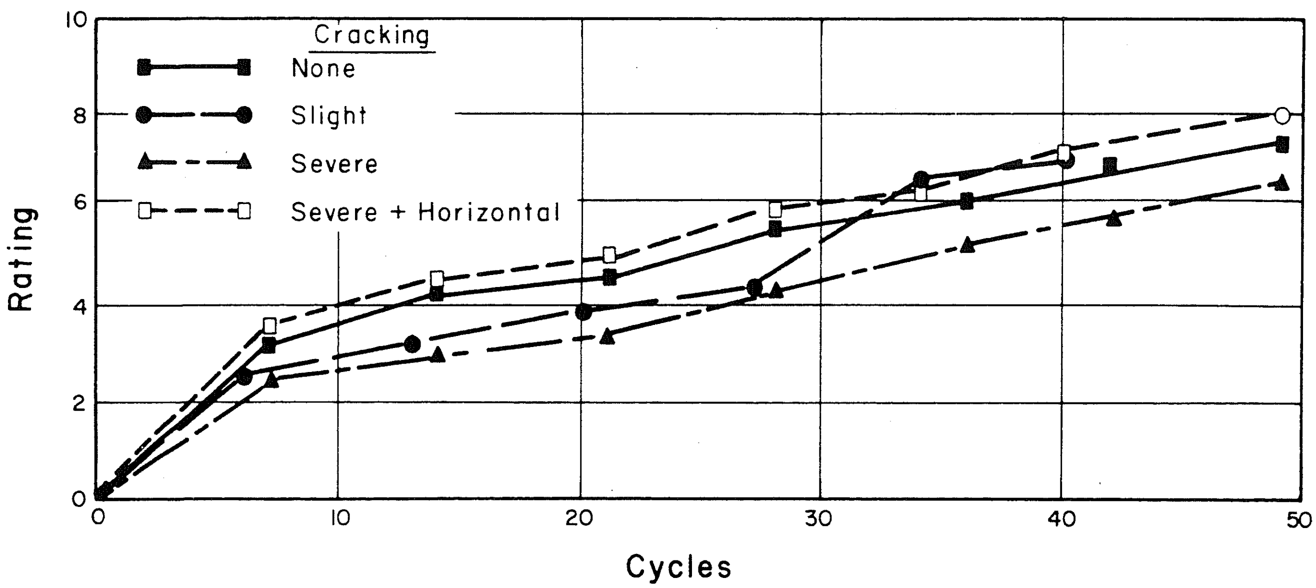


FIG. D39 EFFECT OF EXTENT OF CRACKING ON SURFACE DETERIORATION OF RETARDED CONCRETE – PHASE 3b – SERIES 1D AND 3D

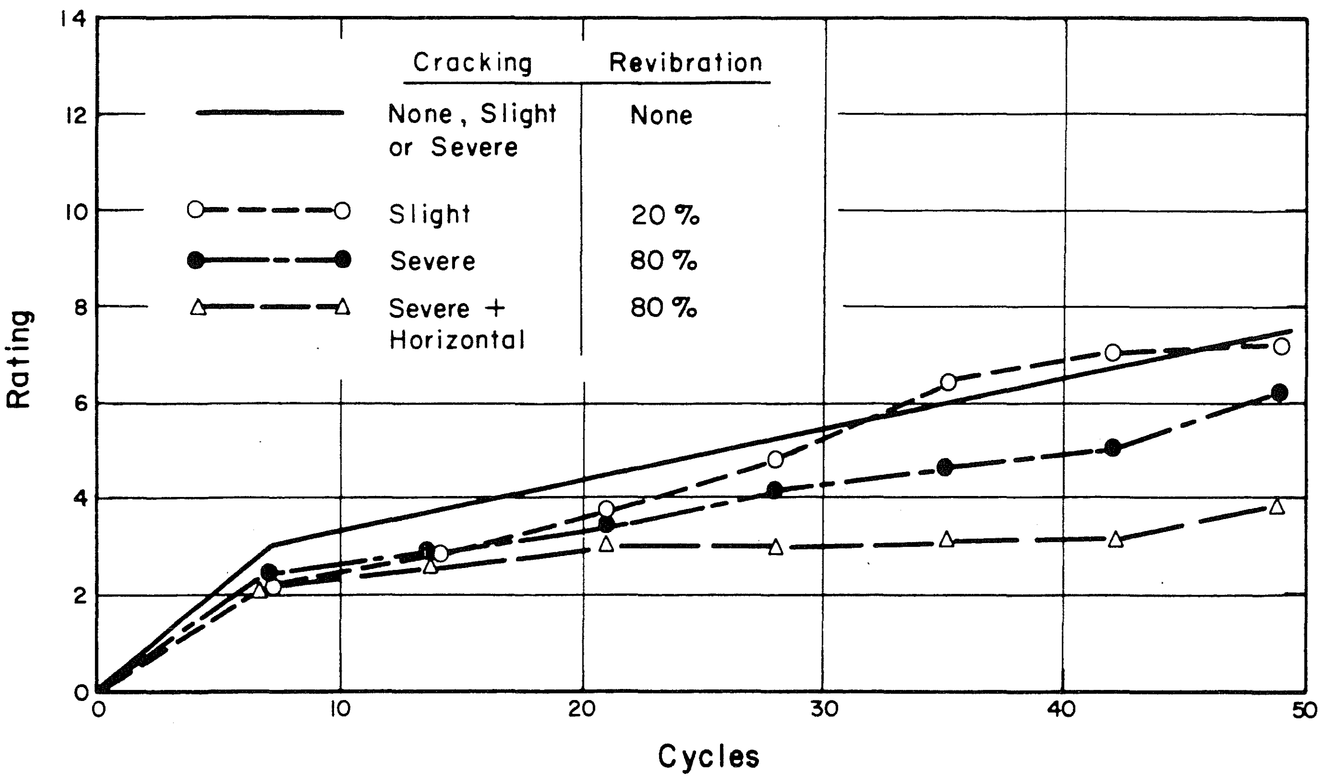
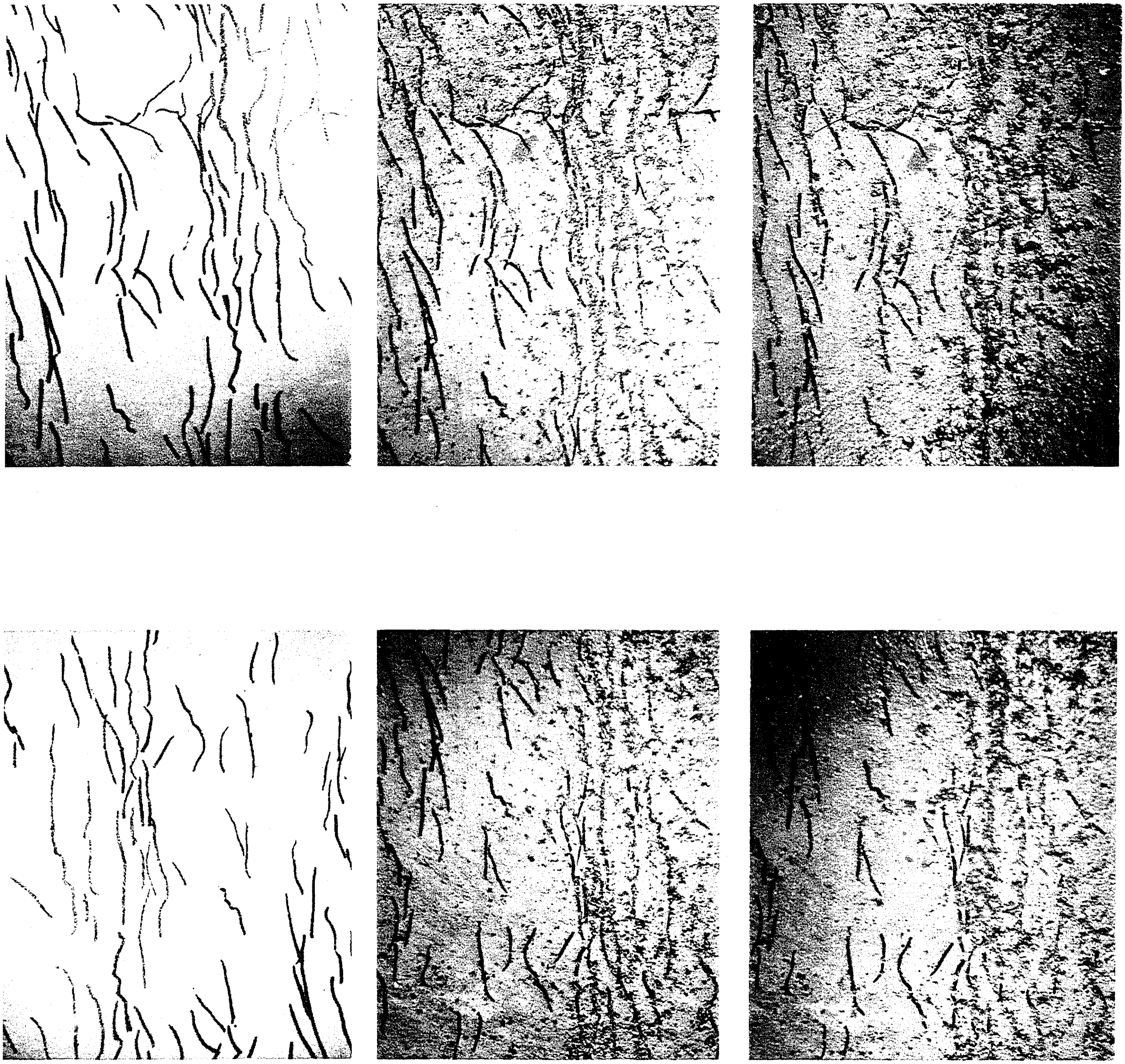


FIG. D40 EFFECT OF SURFACE REVIBRATION ENERGY ON SURFACE DETERIORATION OF RETARDED CONCRETE – PHASE 3b – SERIES 1D AND 3D

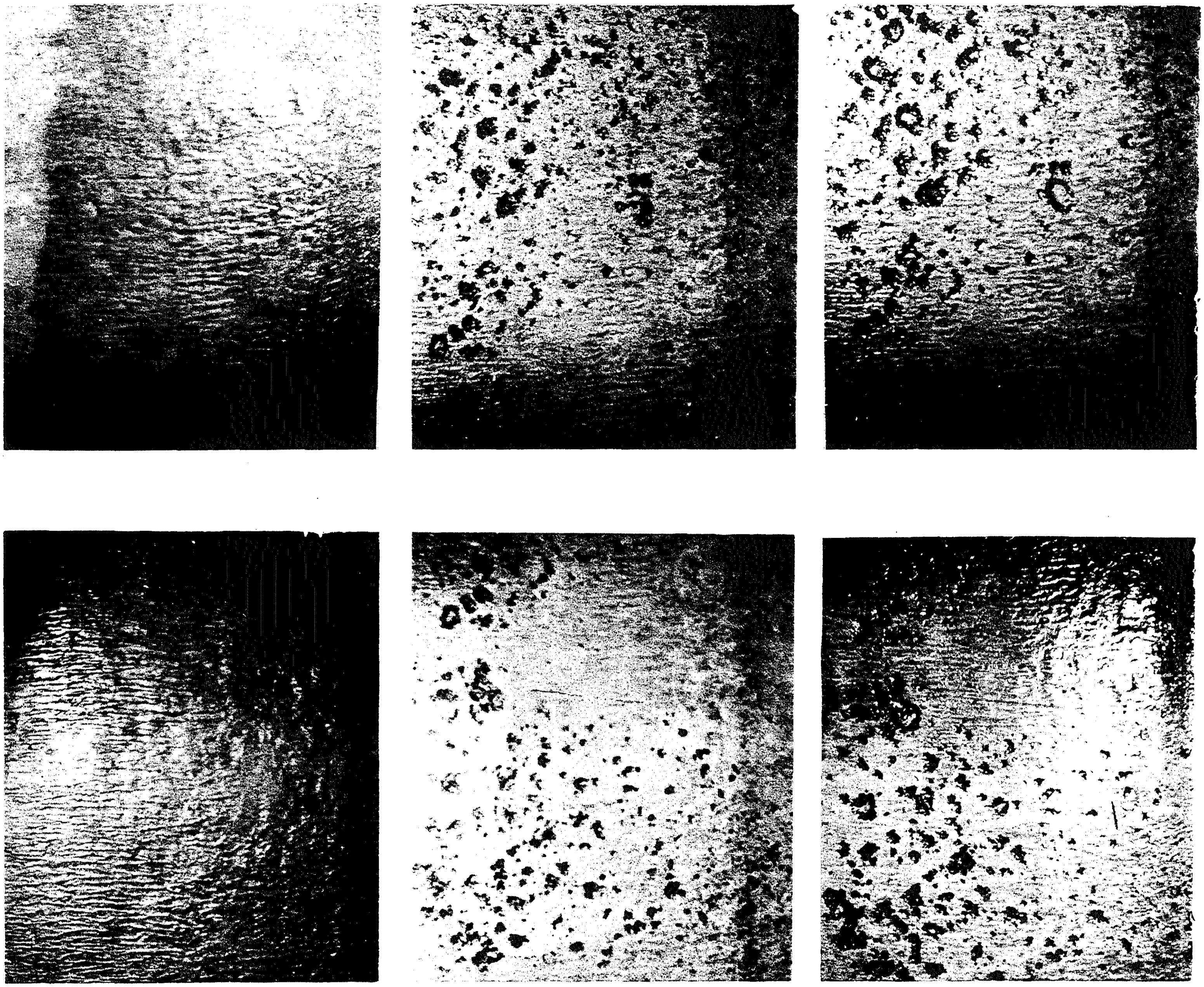


ycles : 0
ating : 0

Cycles : 7
Rating : 2-1/2

Cycles : 21
Rating : 4

IG. D41a SURFACE DETERIORATION OF SPECIMEN SUD-SE-OA PHASE 3b
SERIES 1D — NO REVIBRATION — SEVERE CRACKING



Cycles : 0
Rating : 0

Cycles : 7
Rating : 2

Cycles : 21
Rating : 3

FIG. D41b SURFACE DETERIORATION OF SPECIMEN SUD-SE-80 PHASE 3b
SERIES ID – SURFACE REVIBRATION – ENERGY LEVEL 80 %

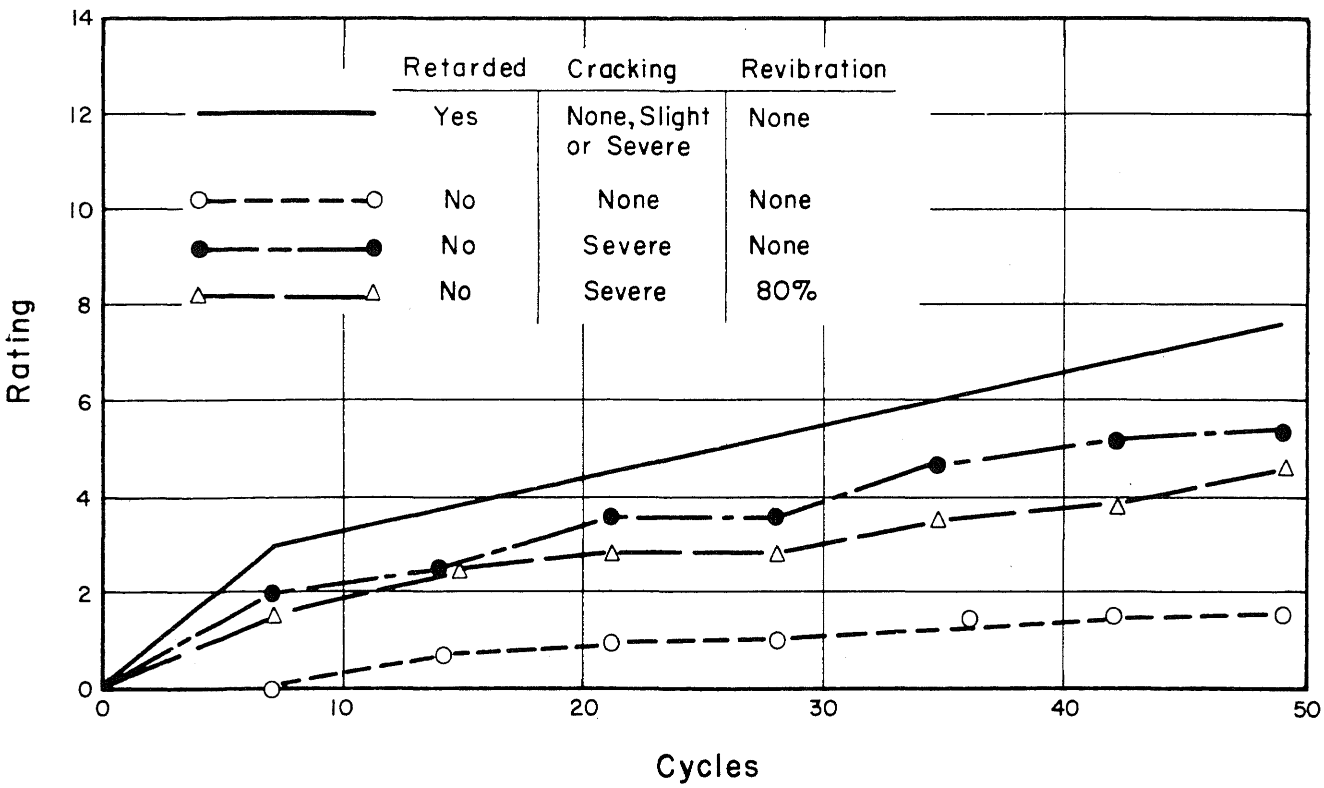


FIG. D42 EFFECT OF SURFACE REVIBRATION ENERGY ON SURFACE DETERIORATION OF NON-RETARDED CONCRETE — PHASE 3b — SERIES 2D

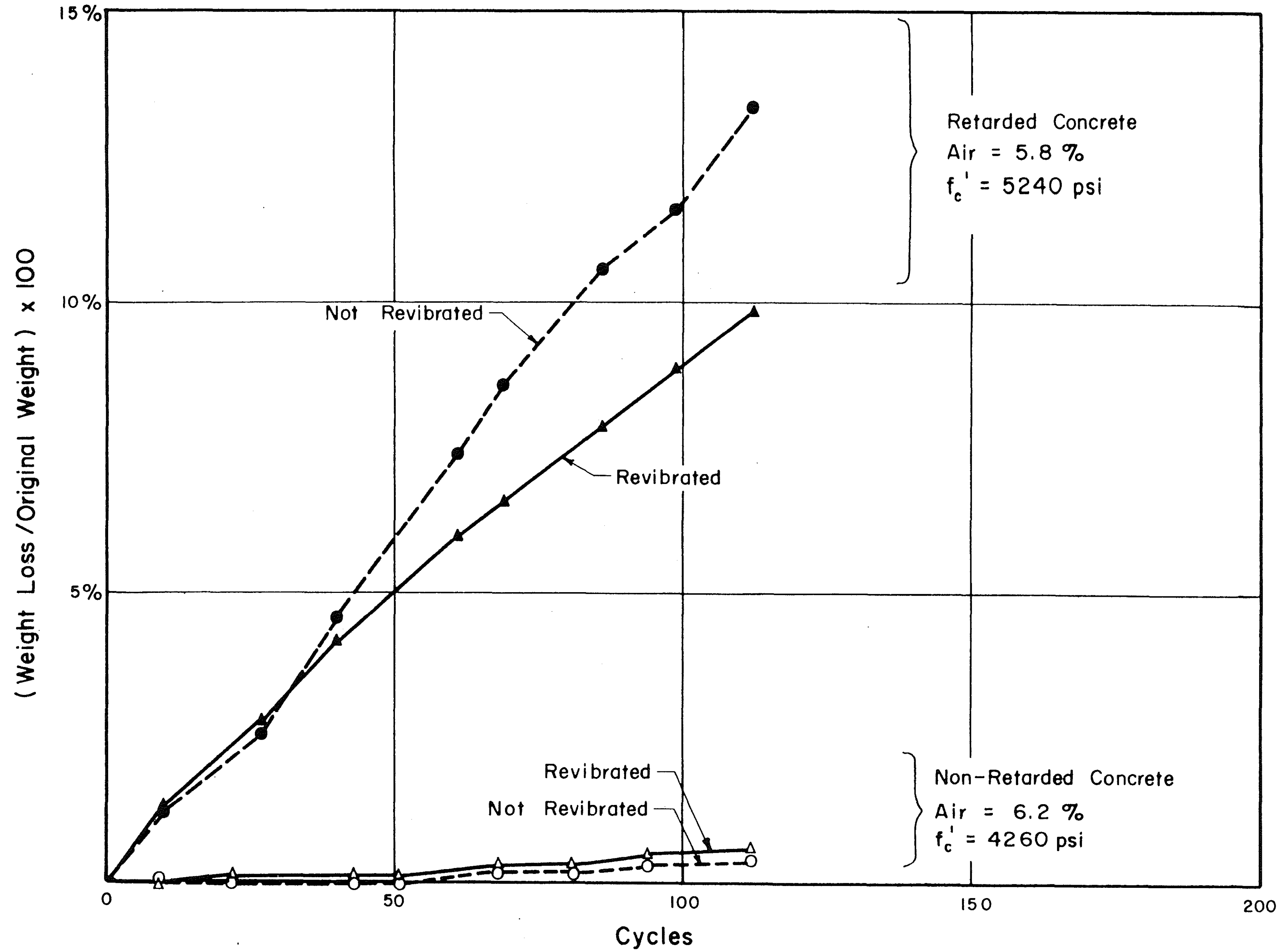


FIG. D 43 FREEZING AND THAWING RESISTANCE OF RETARDED AND NON-RETARDED CONCRETE

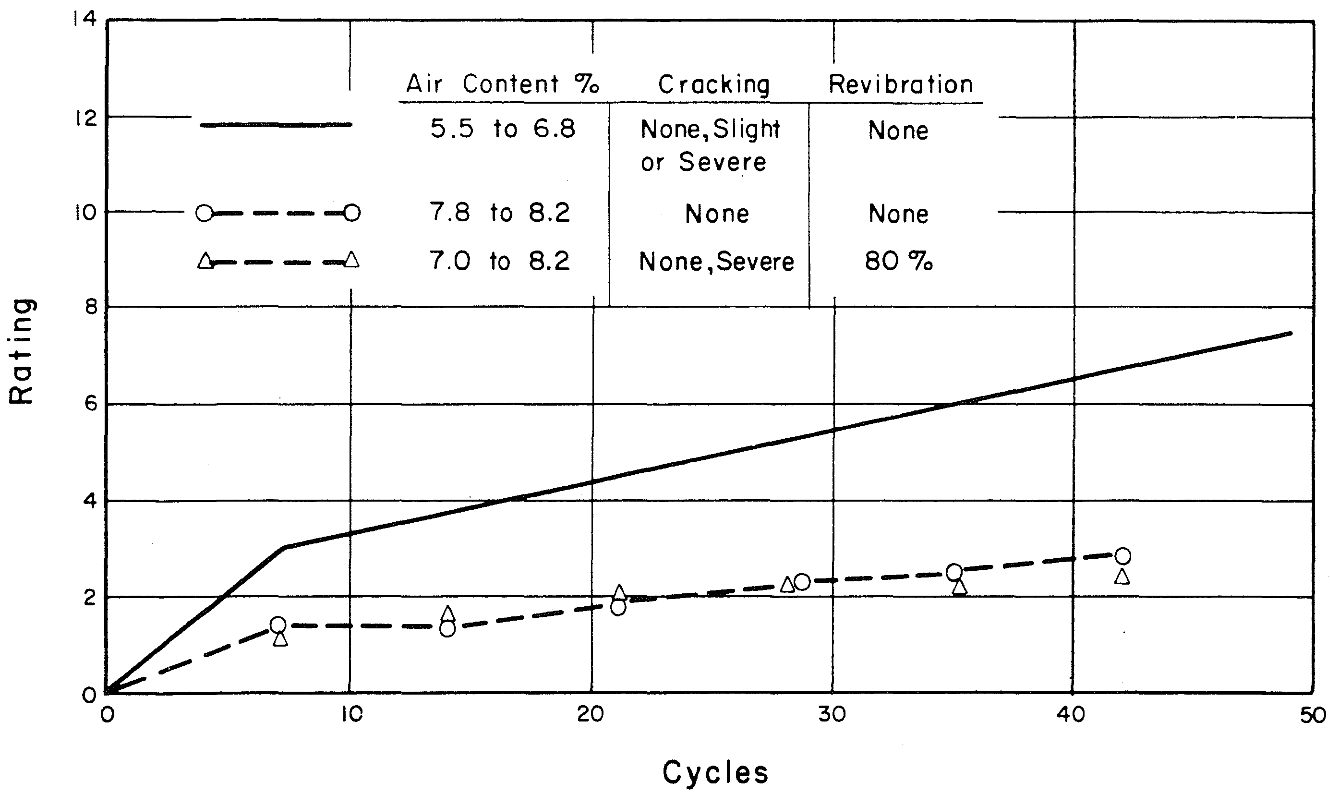


FIG. D44 EFFECT OF INCREASED AIR CONTENT OF RETARDED CONCRETE ON SURFACE DETERIORATION – PHASE 3b – SERIES 4D

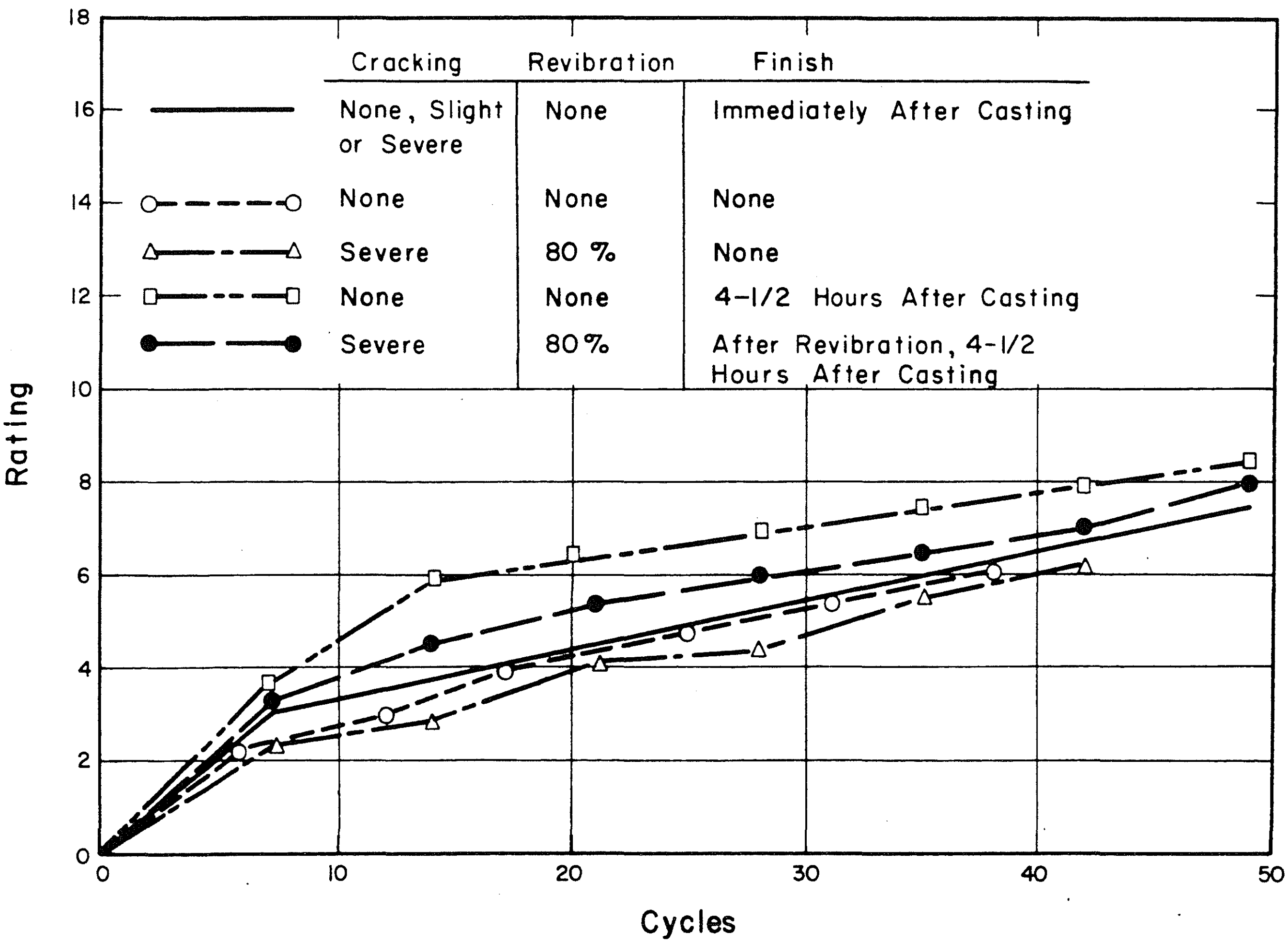
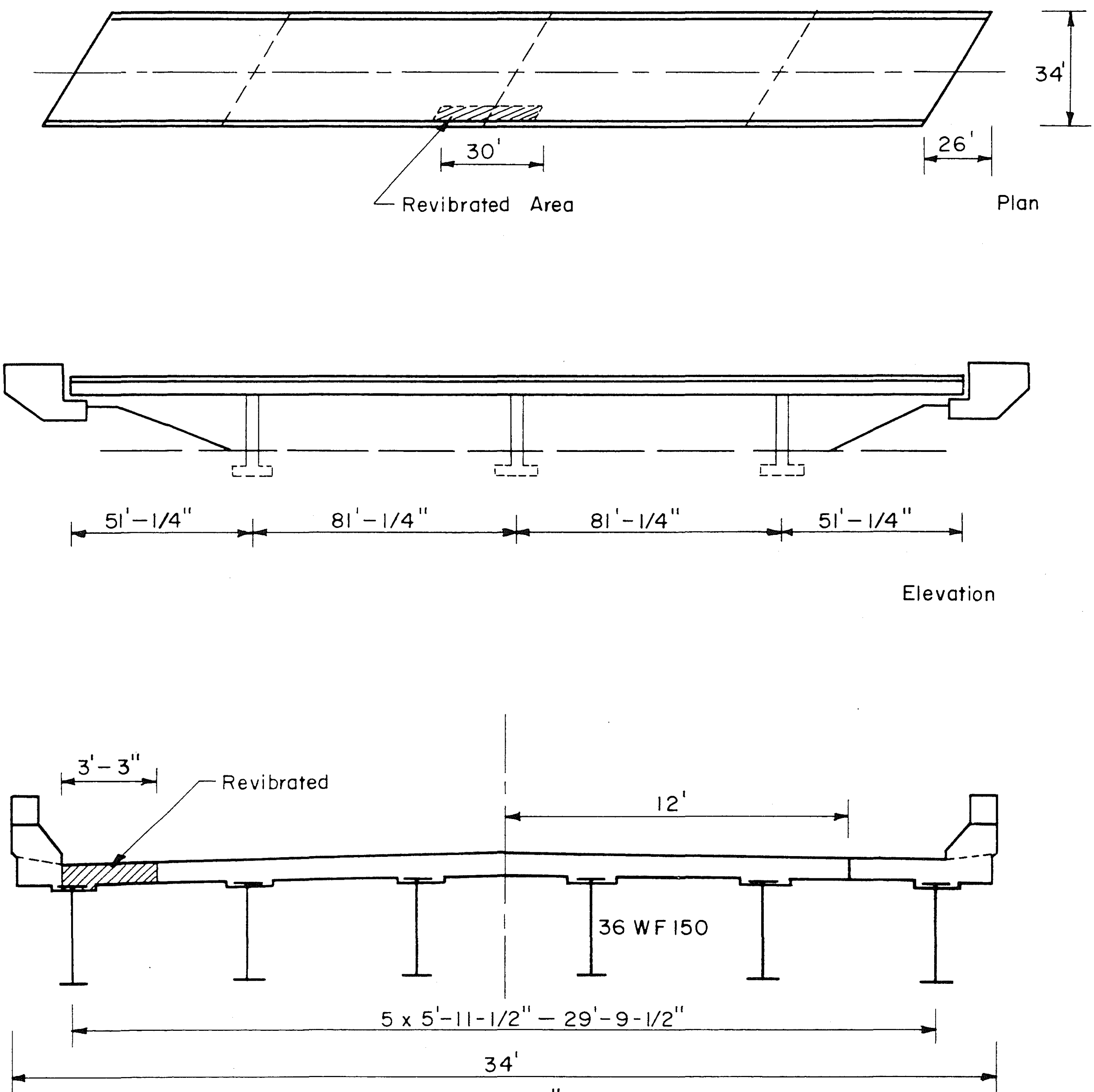


FIG. D45 EFFECT OF FINISHING PROCEDURES ON SURFACE DETERIORATION OF RETARDED CONCRETE — PHASE 3b — SERIES 5D



Concrete Cover Above Reinforcement : 2"
Reinforcement in Revibrated Section : Transverse : Top # 5 at 6.5"
Bottom # 5 at 6.5"
Longitudinal : Top # 5 at 12"
and # 6 at 12"
Bottom : # 5 at 10"

FIG. E46 CROSS SECTION OF BRIDGE FOR THE FIELD EXPERIMENT NEAR CHAMPAIGN, ILLINOIS

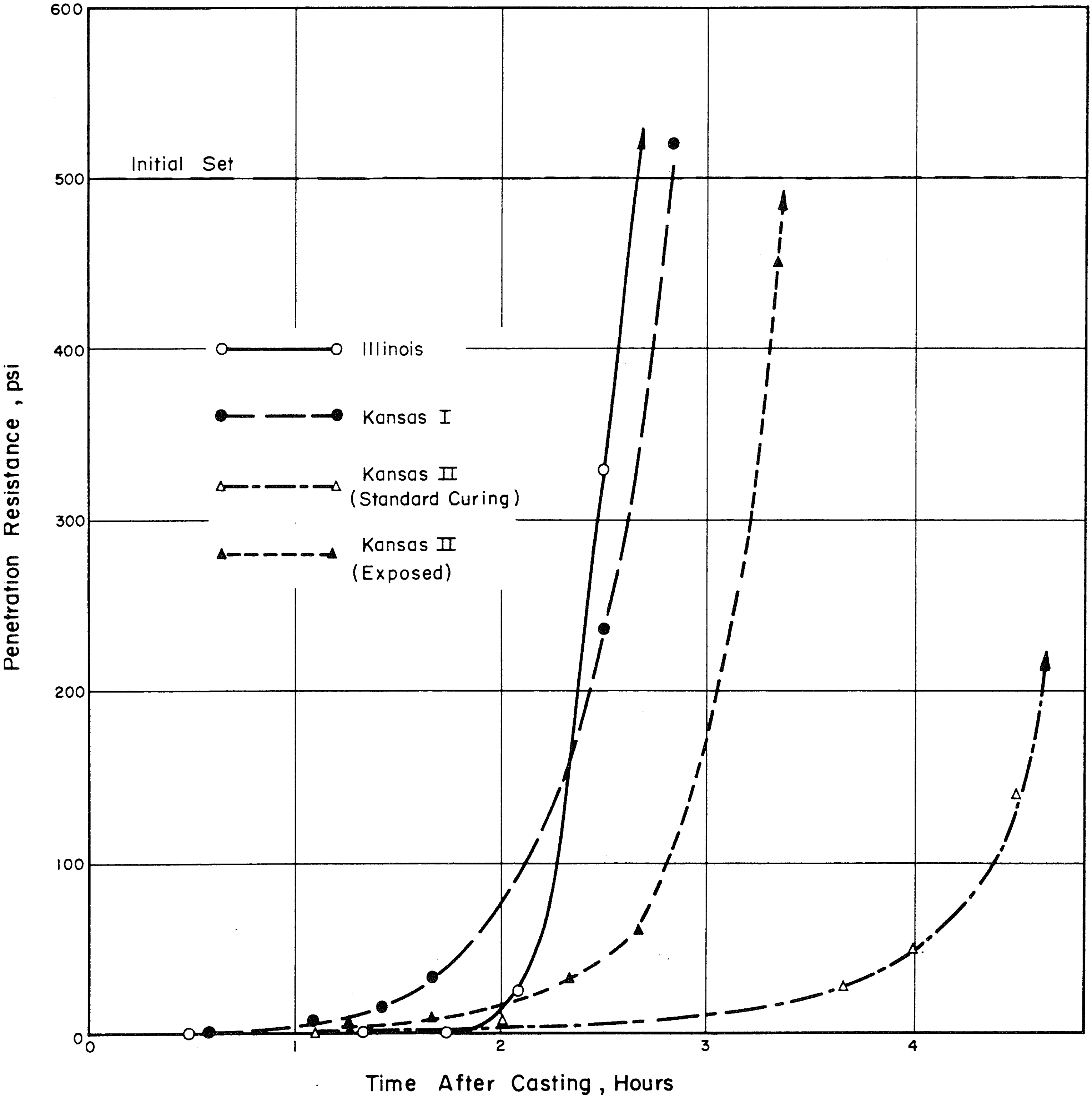


FIG. E47 PENETRATION RESISTANCE OF BRIDGE DECK CONCRETE

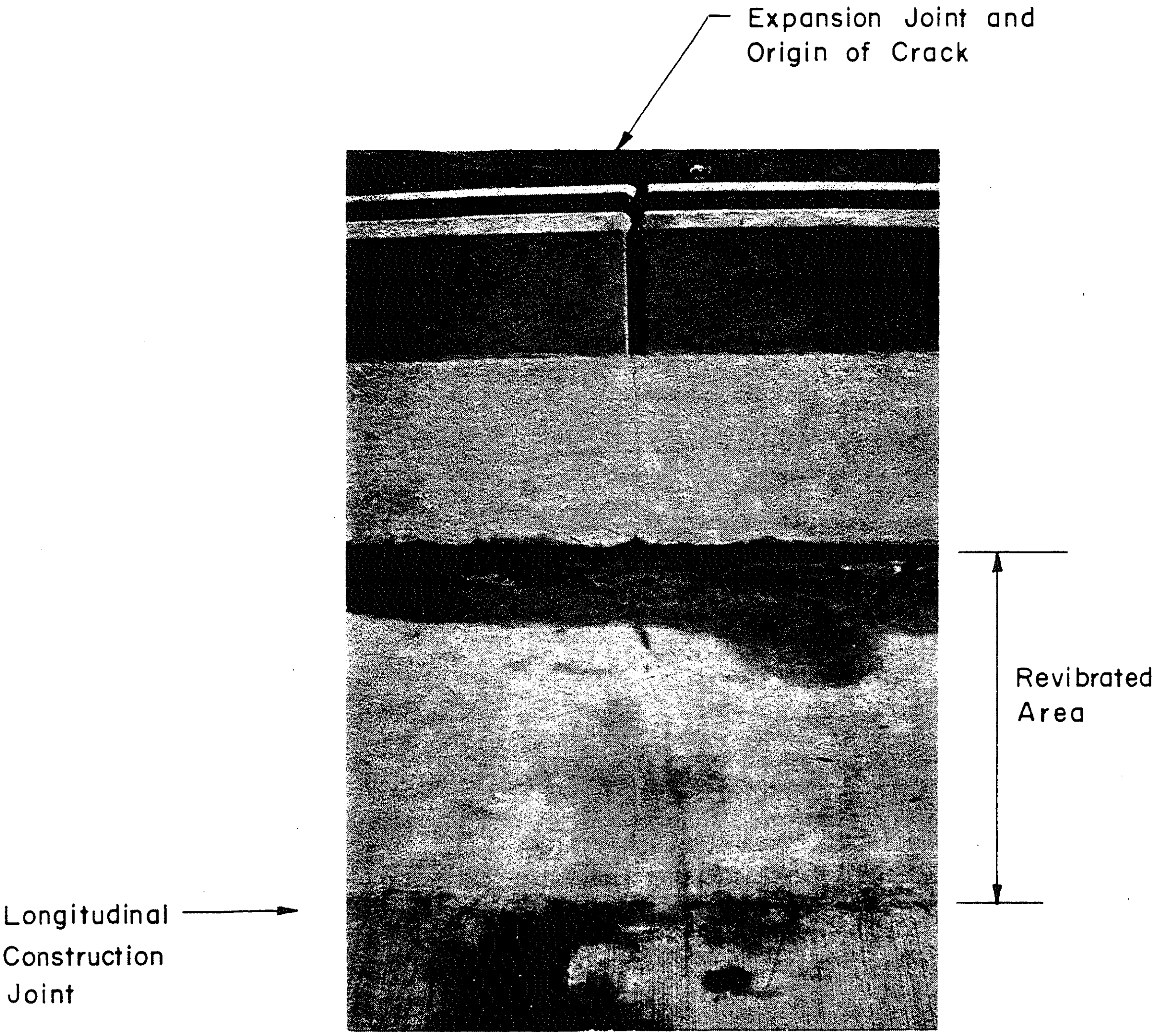
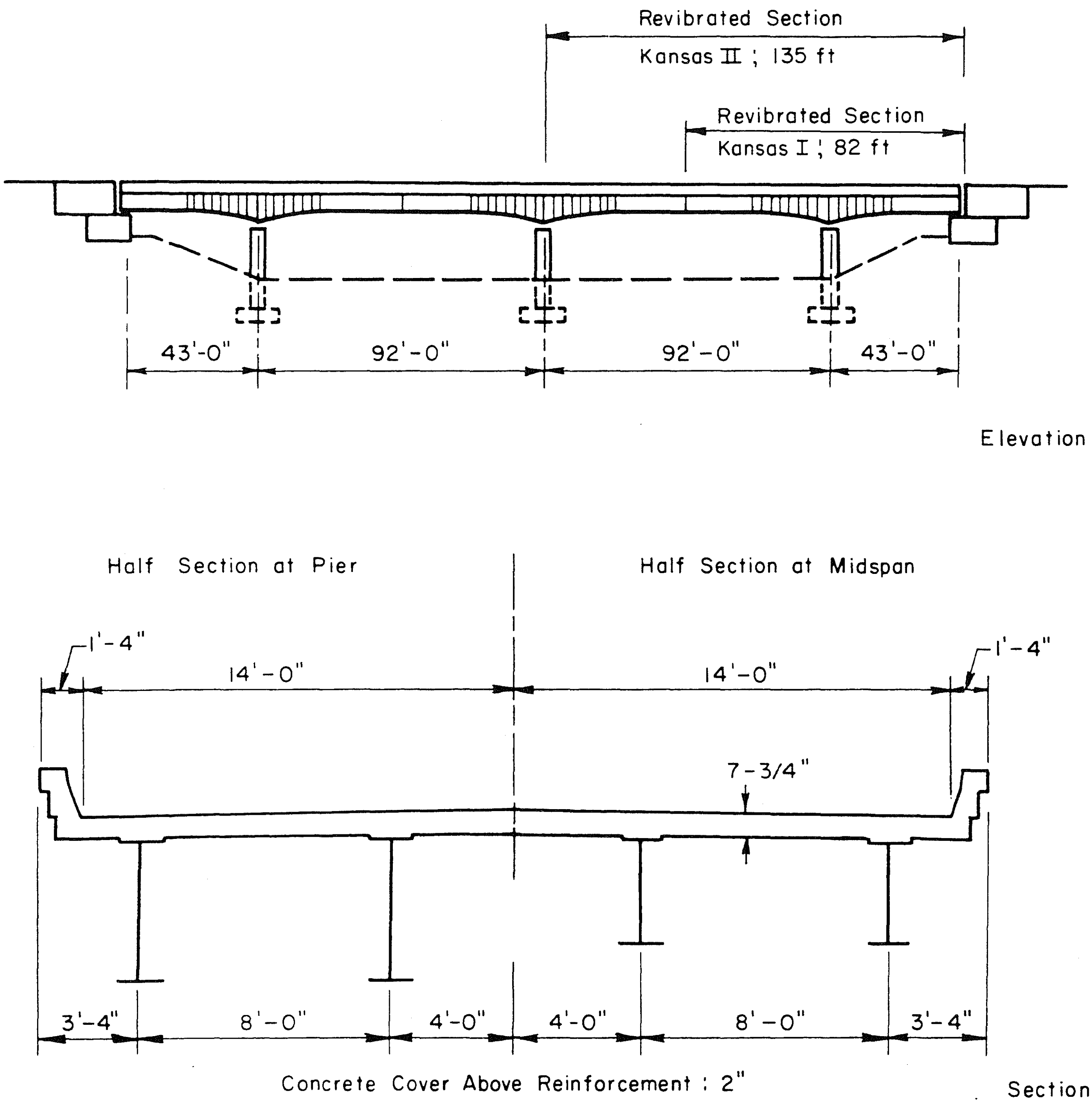


FIG. E 48 HAIRLINE CRACK IN REVIBRATED BRIDGE DECK NEAR CHAMPAIGN, ILLINOIS



Reinforcement :

	Transverse	Longitudinal
	Top – #5 at 5"	Top – #4 at 16"
	Bottom – #4 at 10" and #5 at 10"	Bottom – #4 at 10"

FIG. E49 CROSS SECTION OF BRIDGE FOR THE FIELD EXPERIMENTS NEAR NEWTON, KANSAS

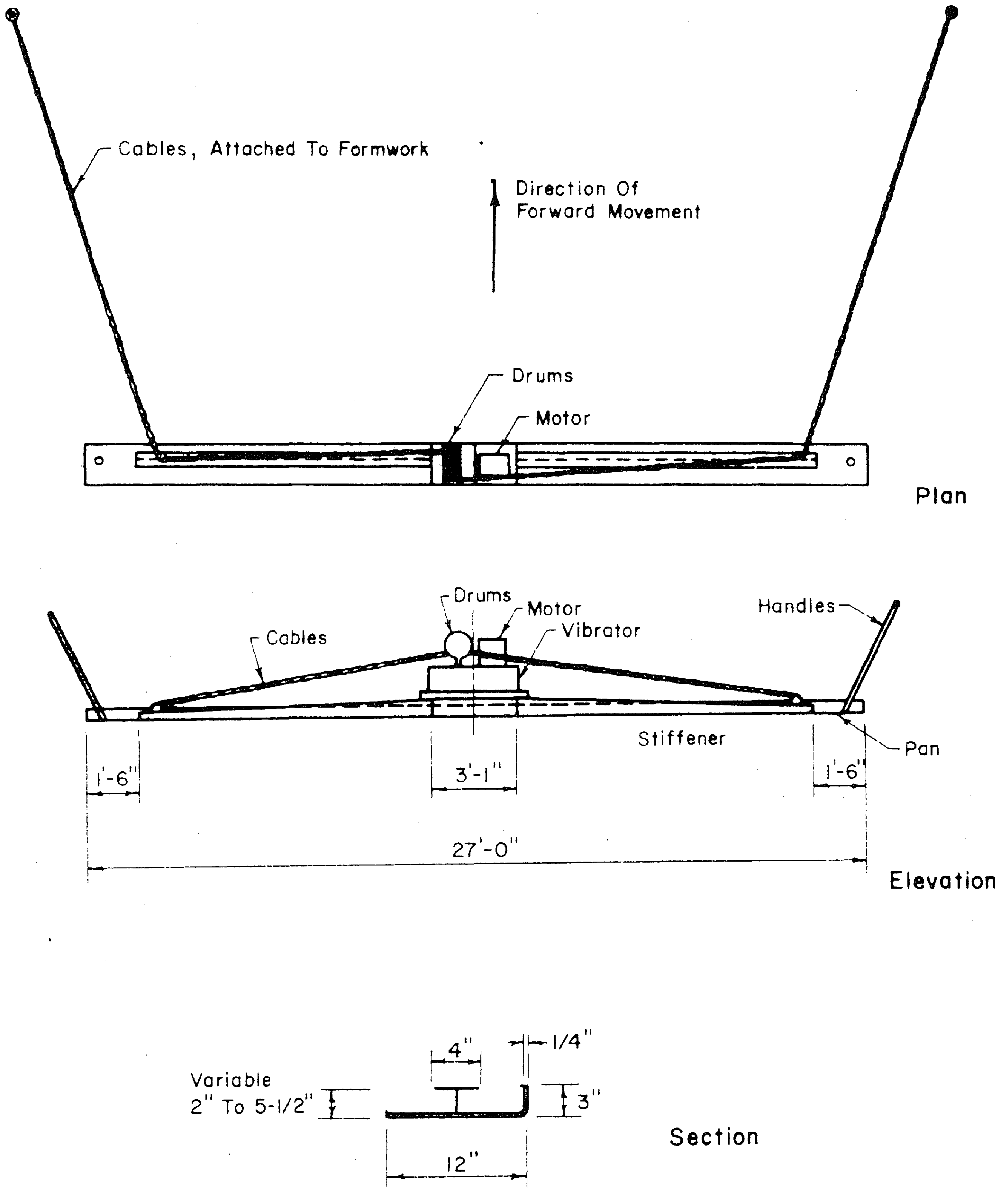


FIG. E50 VIBRATING SCREED USED TO REVIBRATE THE DECK OF BRIDGE NO. 35W-40-2.00 NEAR NEWTON, KANSAS

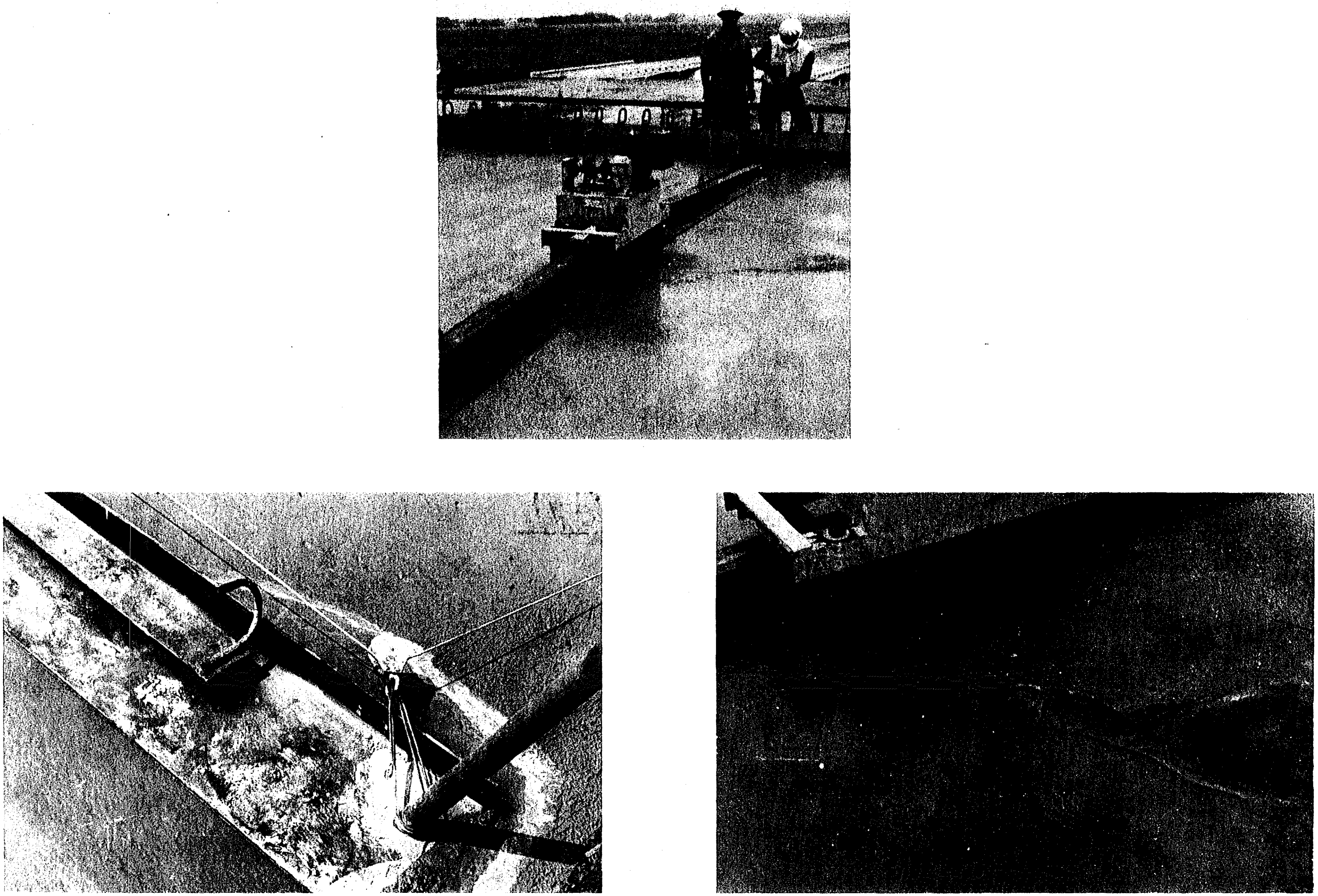


FIG. E51 VIBRATING SCREED AND APPEARANCE OF DECK AFTER REVIBRATION — BRIDGE NO. 35W-40-2.00 NEAR NEWTON, KANSAS

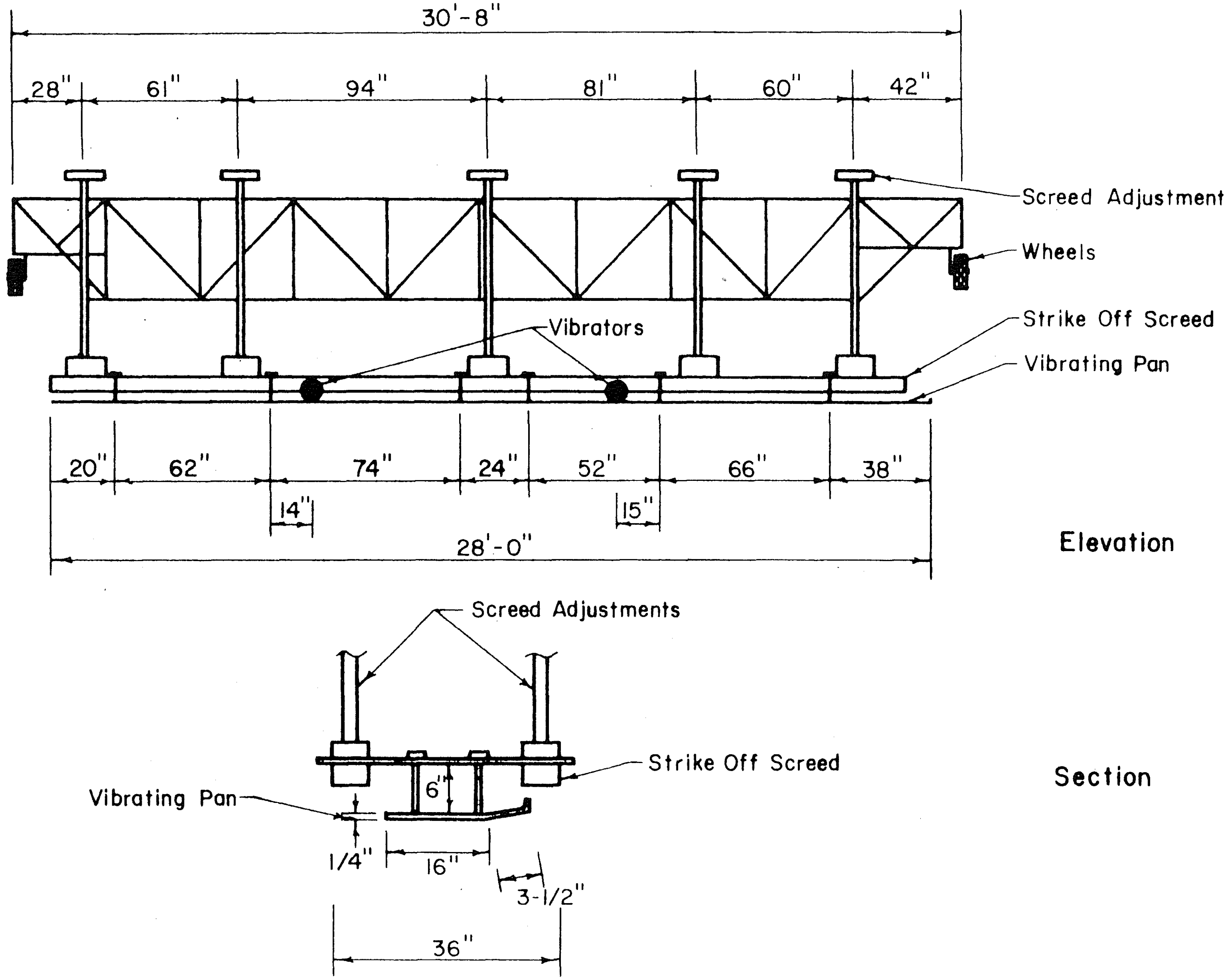
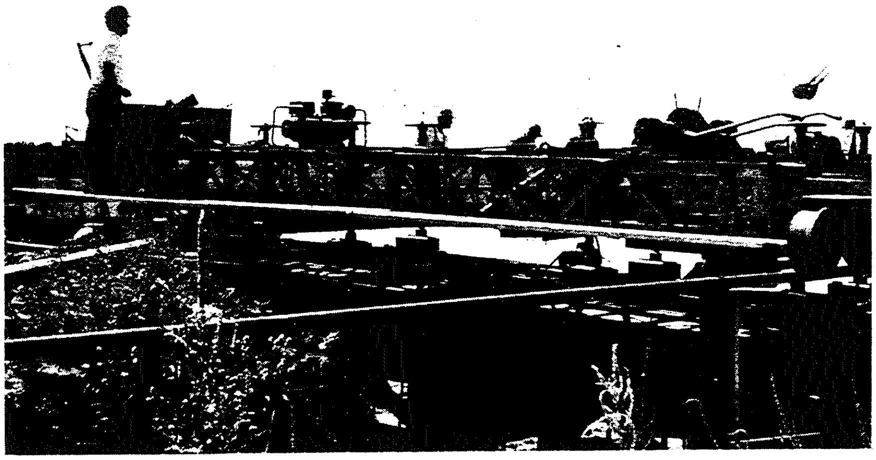


FIG. E 52 a SCHEMATIC PRESENTATION OF VIBRATING SCREED USED TO REVIBRATE DECK OF BRIDGE NO. 35 W–40–5.00 NEAR NEWTON, KANSAS



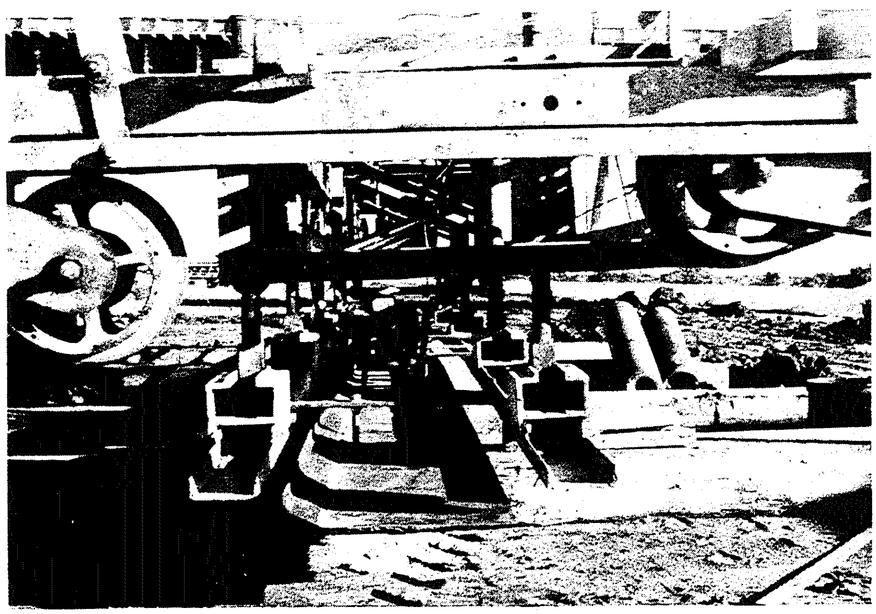


FIG. E52b PHOTOGRAPHS OF VIBRATING SCREED USED FOR REVIBRATION OF BRIDGE DECK NO. 35W-40-5.00

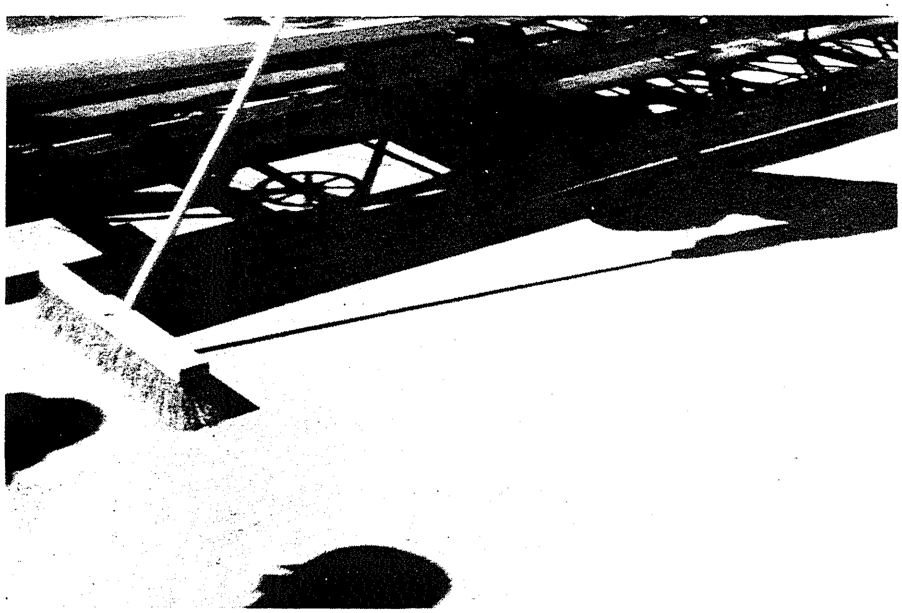


FIG. E53 APPEARANCE OF BRIDGE DECK NO. 35W-40-5.00
AFTER REVIBRATION

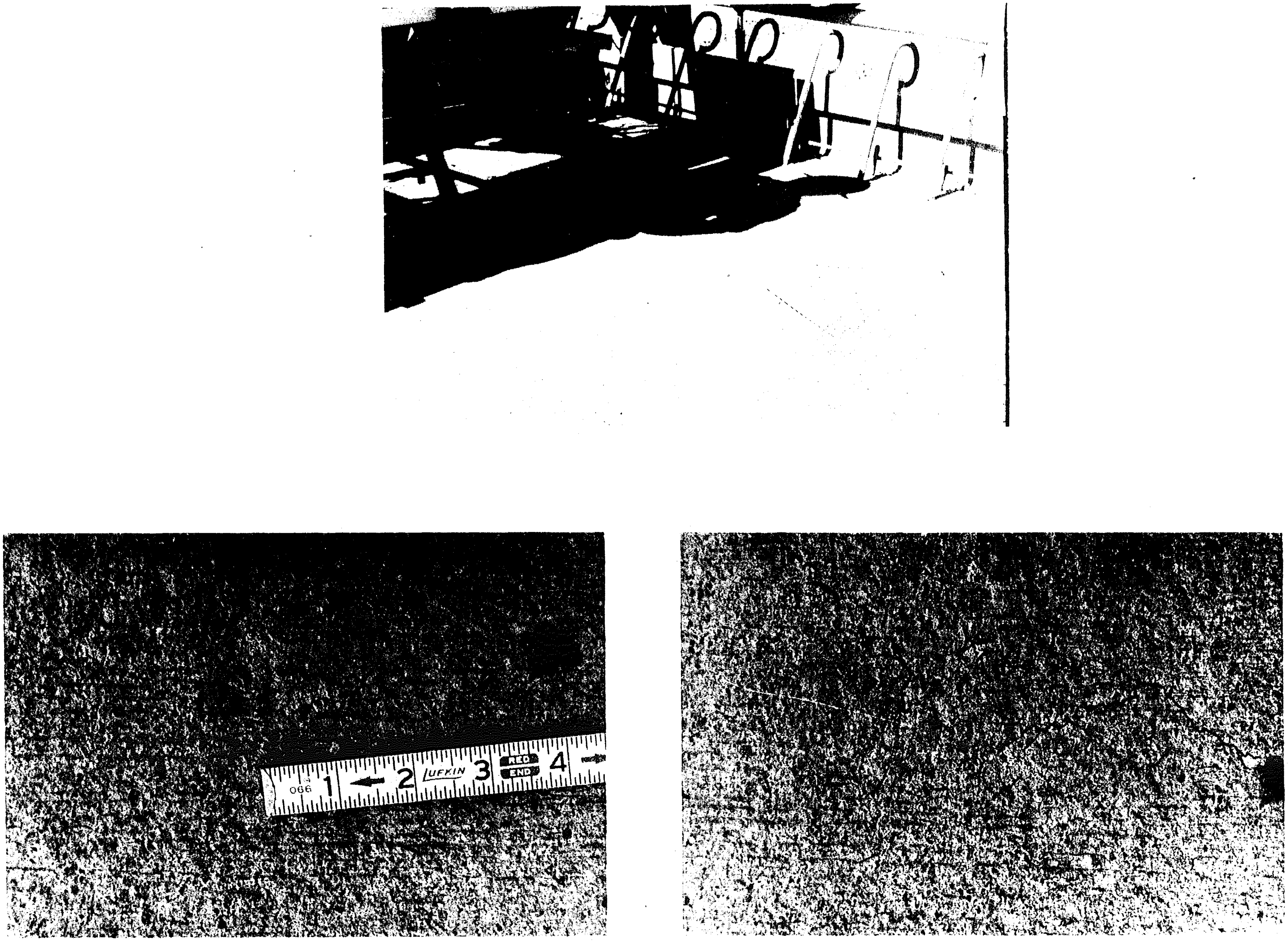


FIG. E54 CRACKS AFTER REVIBRATION OF SURFACE CRUSTED CONCRETE, BRIDGE DECK NO. 35 W – 40 – 5.00

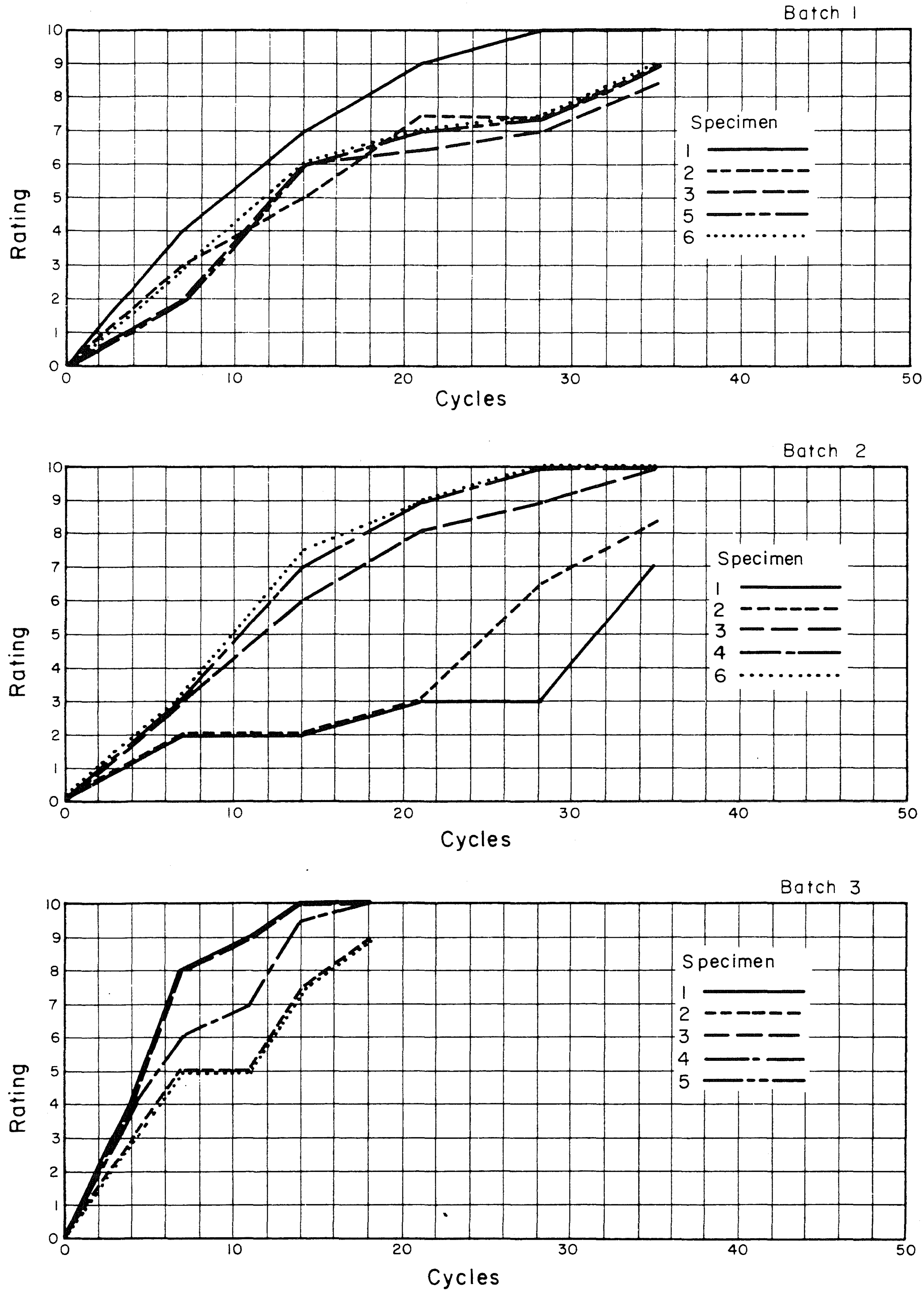
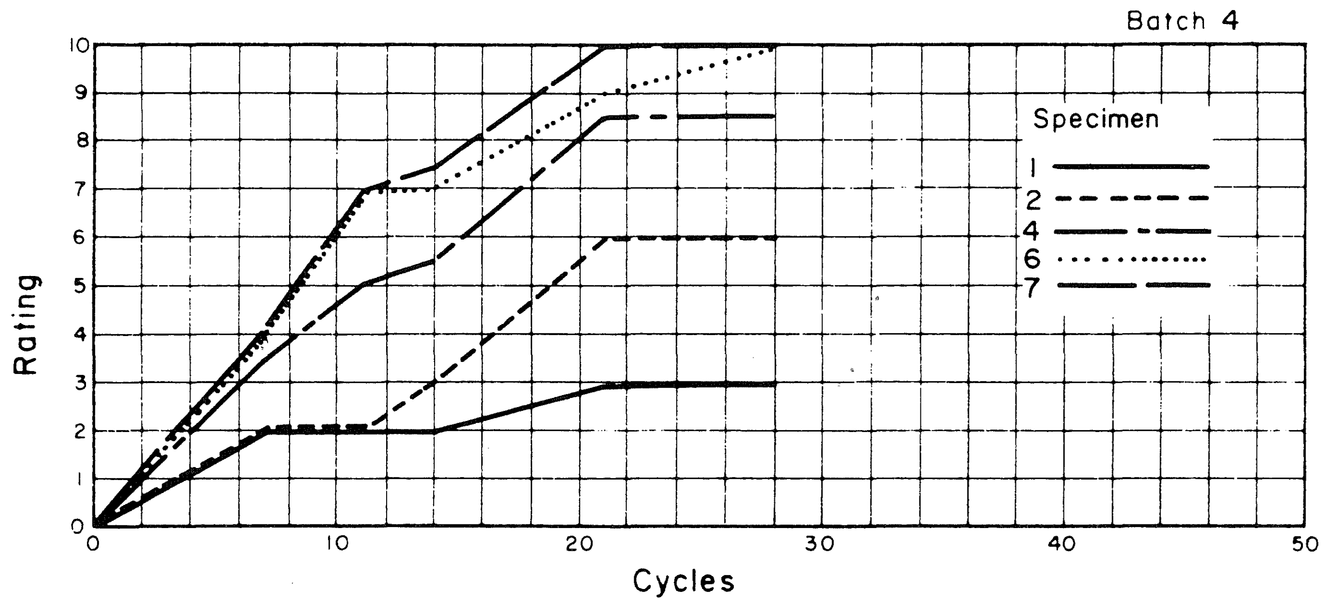


FIG. F 55 INDIVIDUAL TEST RESULTS, SERIES I A — PHASE 3A BATCH 1 – 3



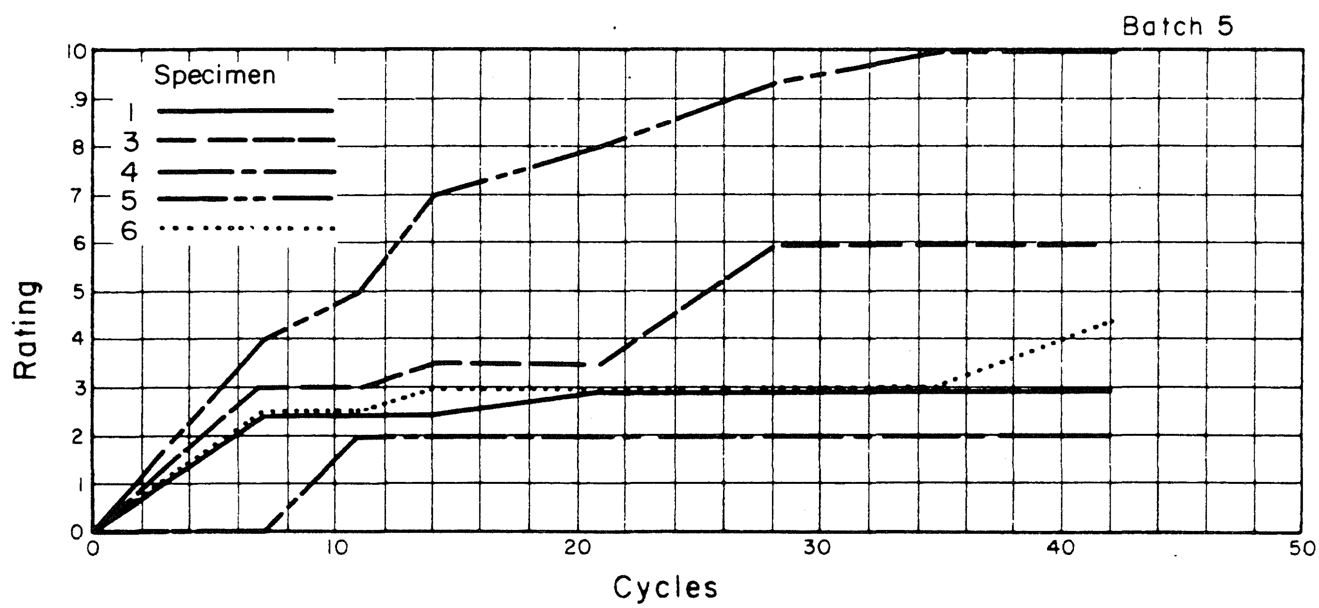


FIG. F56 INDIVIDUAL TEST RESULTS, SERIES 1A — -PHASE 3A
BATCH 4 AND 5

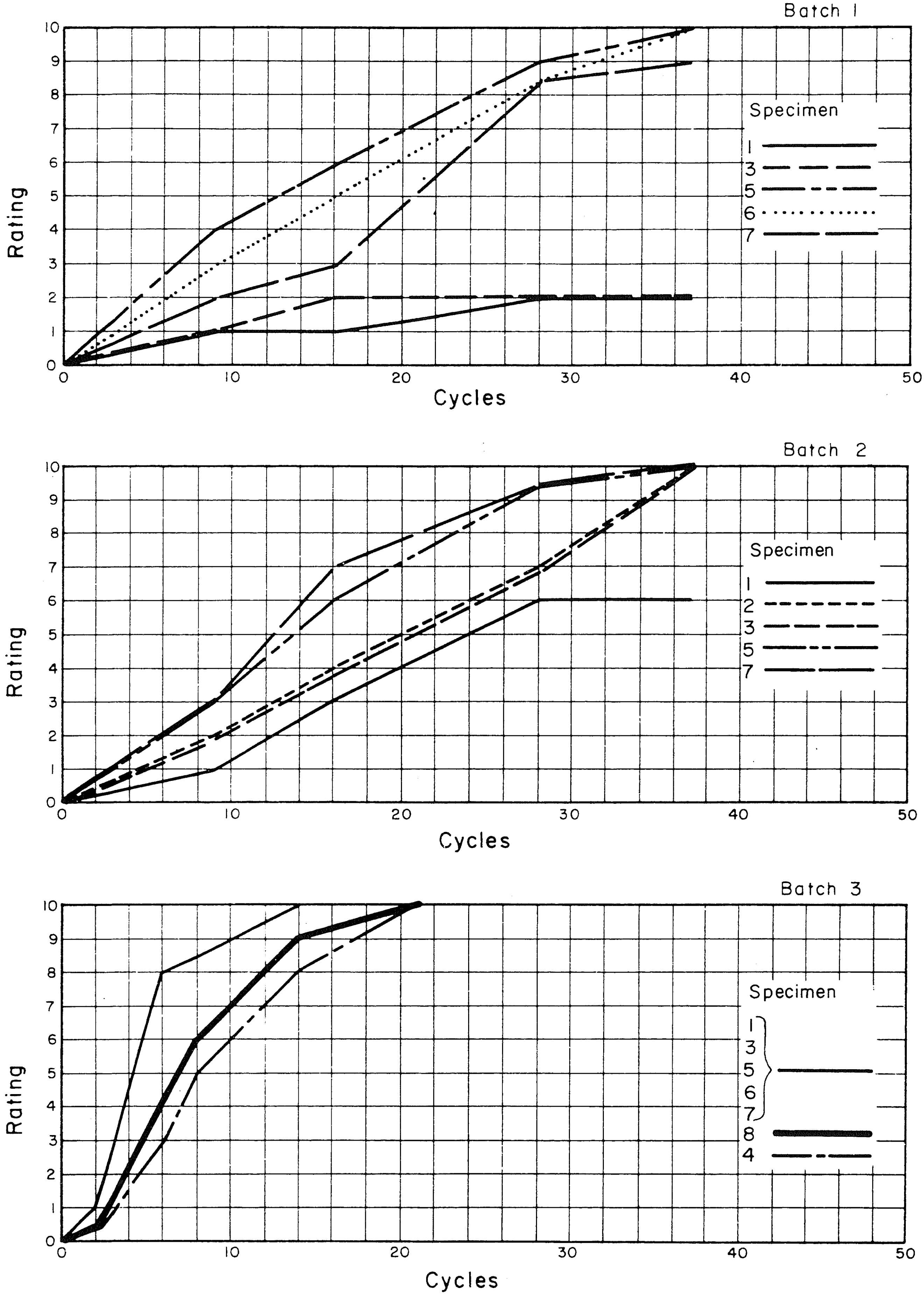
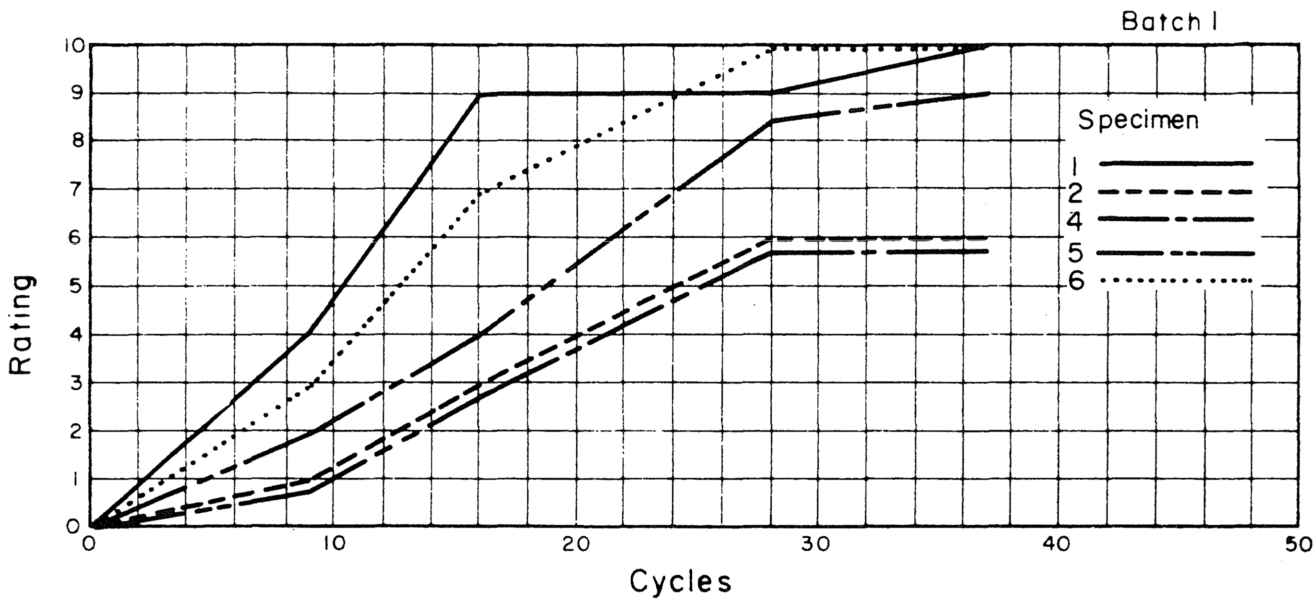


FIG. F57 INDIVIDUAL TEST RESULTS, SERIES 2A — PHASE 3a



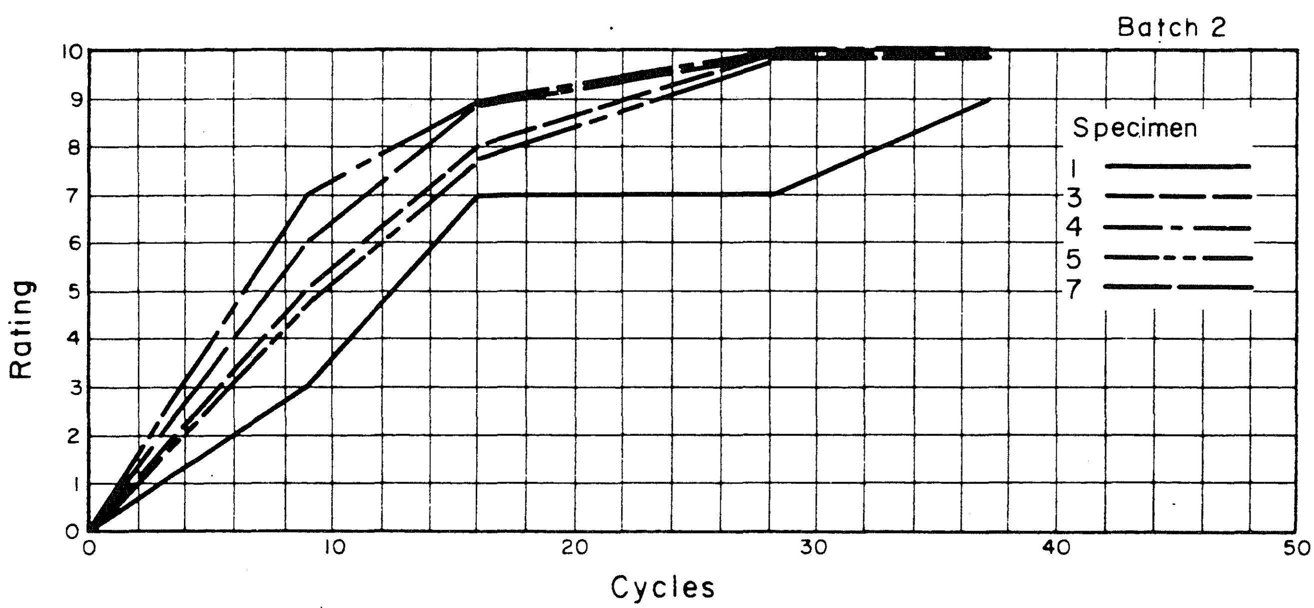
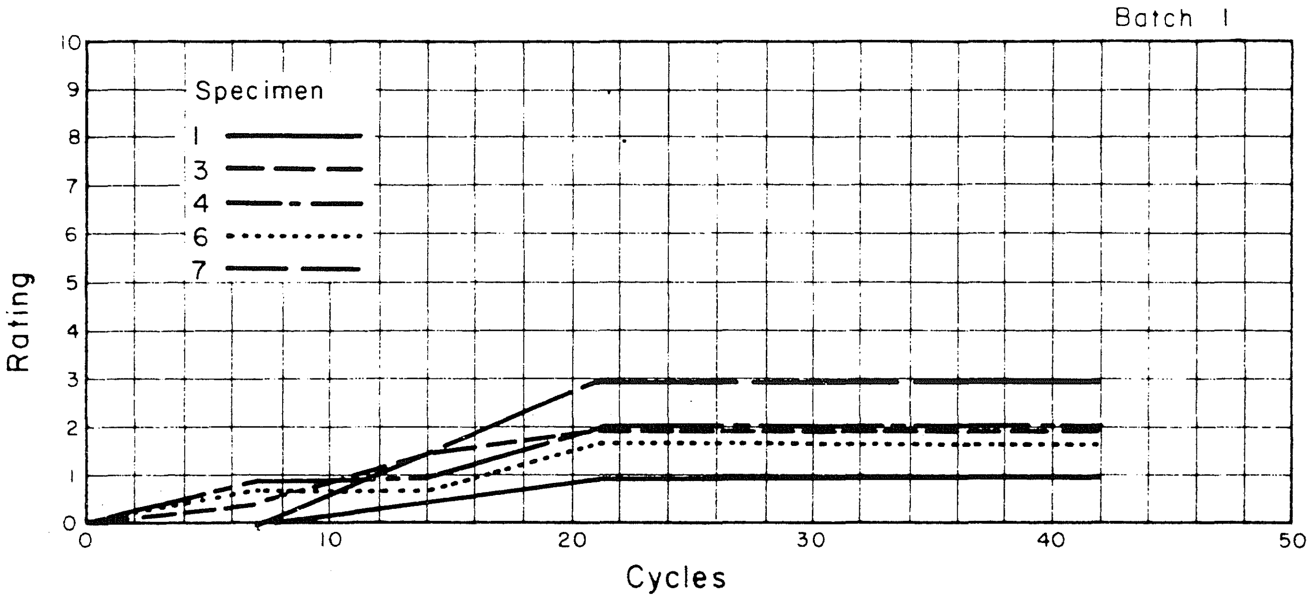


FIG. **F58** INDIVIDUAL TEST RESULTS, SERIES 2 B — PHASE 3a



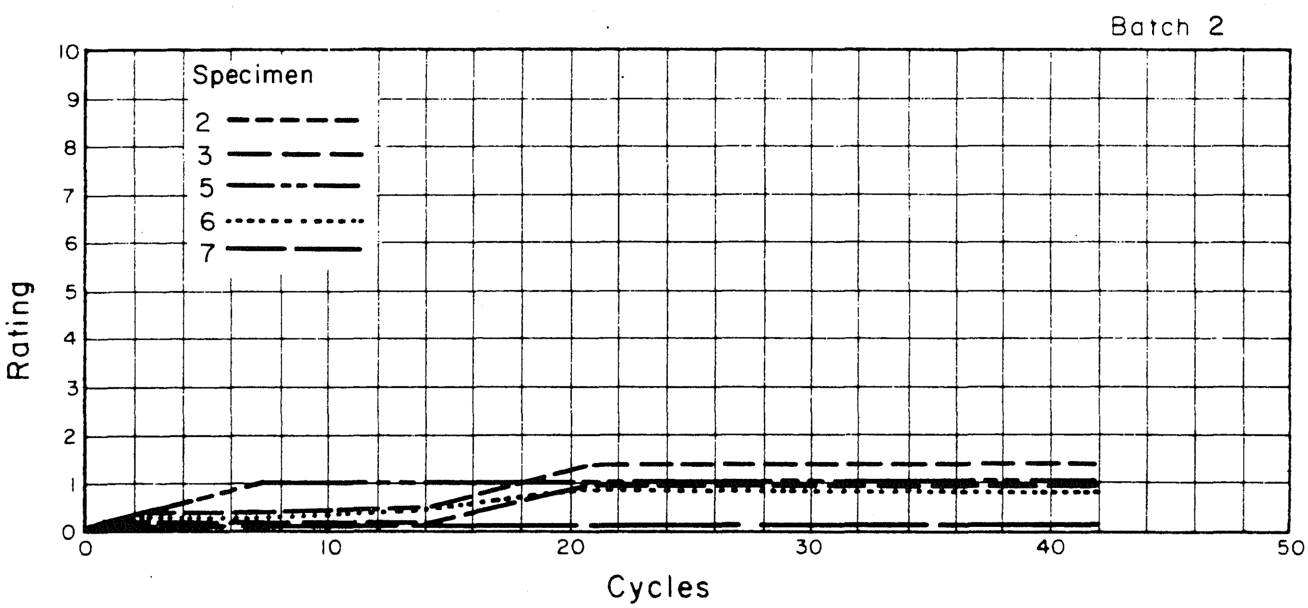


FIG. F59 INDIVIDUAL TEST RESULTS, SERIES 2C —— PHASE 3a

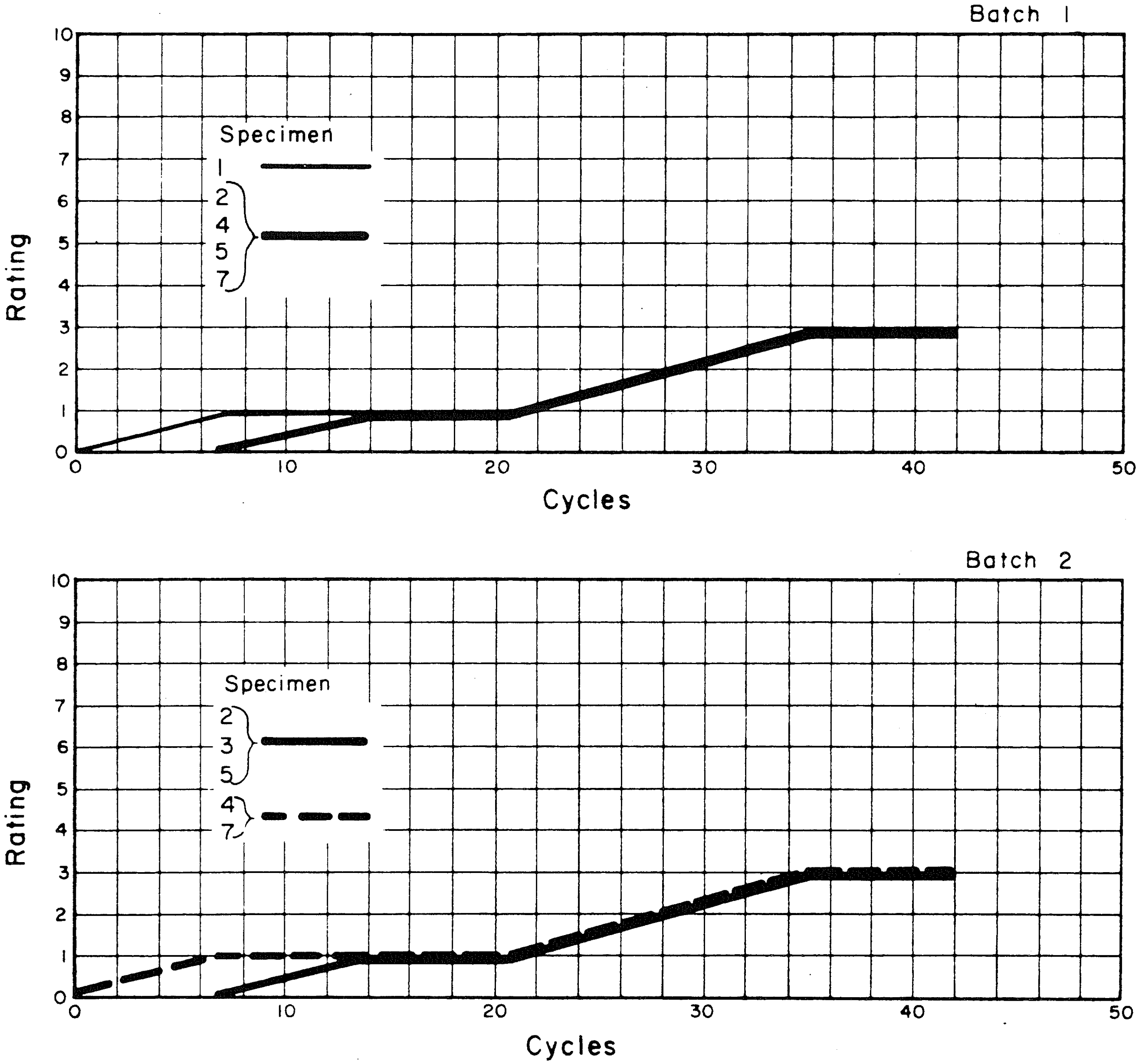


FIG. **F60** INDIVIDUAL TEST RESULTS, SERIES 3 — **PHASE 3a**

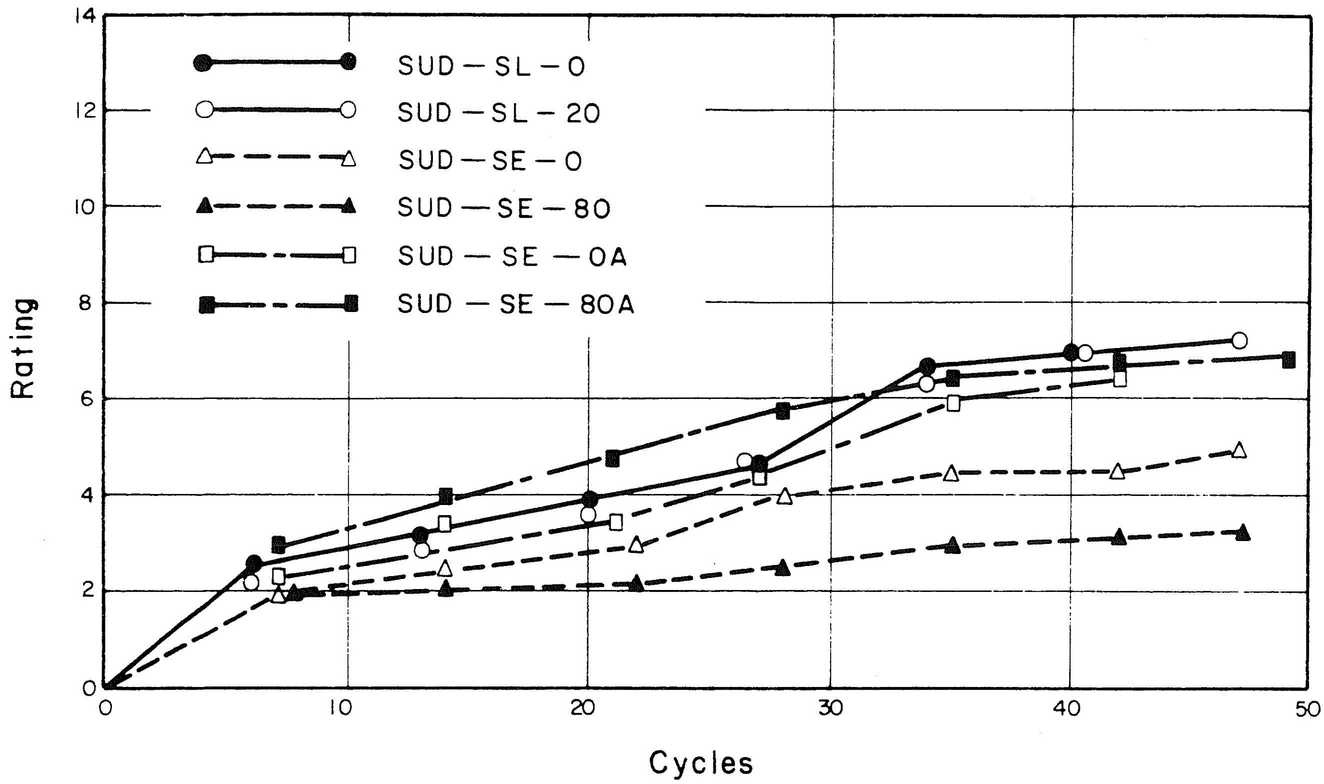


FIG. F61 INDIVIDUAL TEST RESULTS - SERIES 1D - PHASE 3b

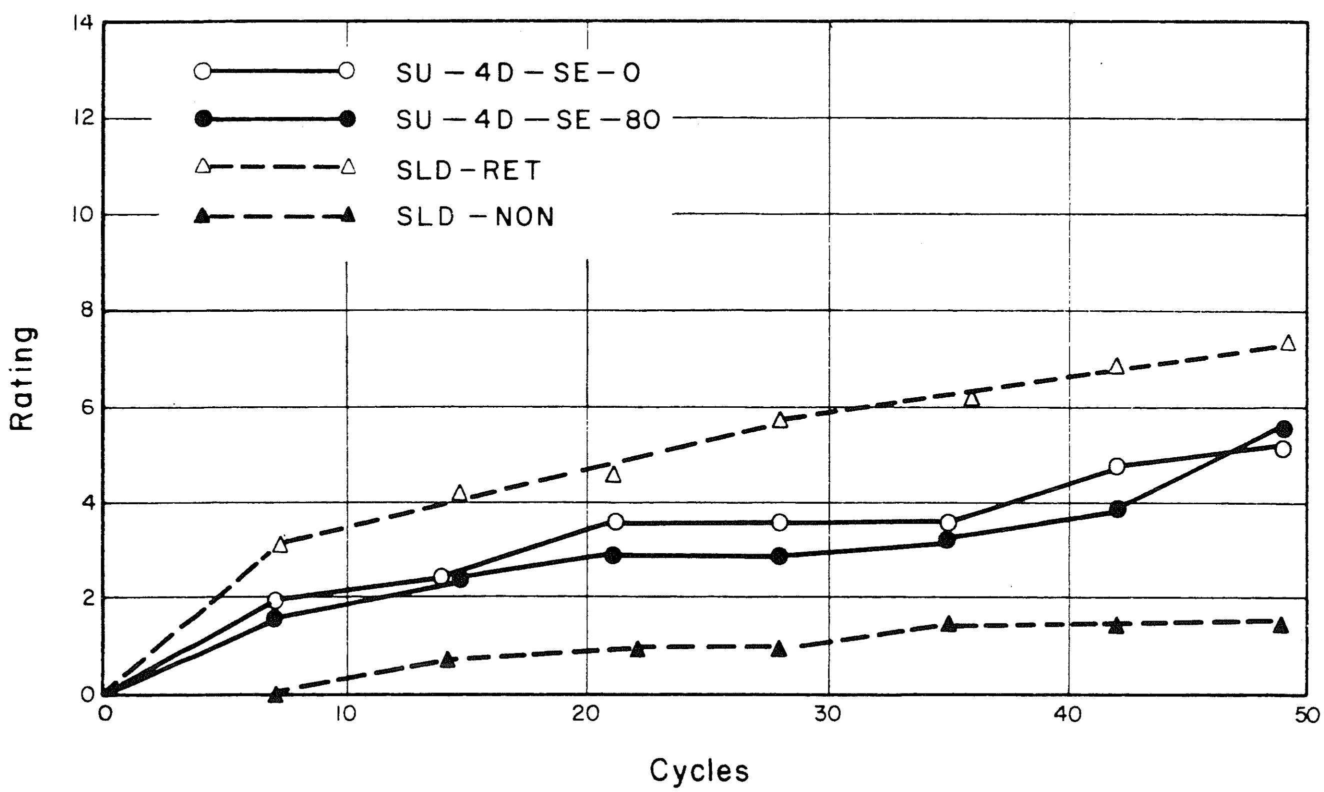


FIG. F62 INDIVIDUAL TEST RESULTS - SERIES 2D - PHASE 3b

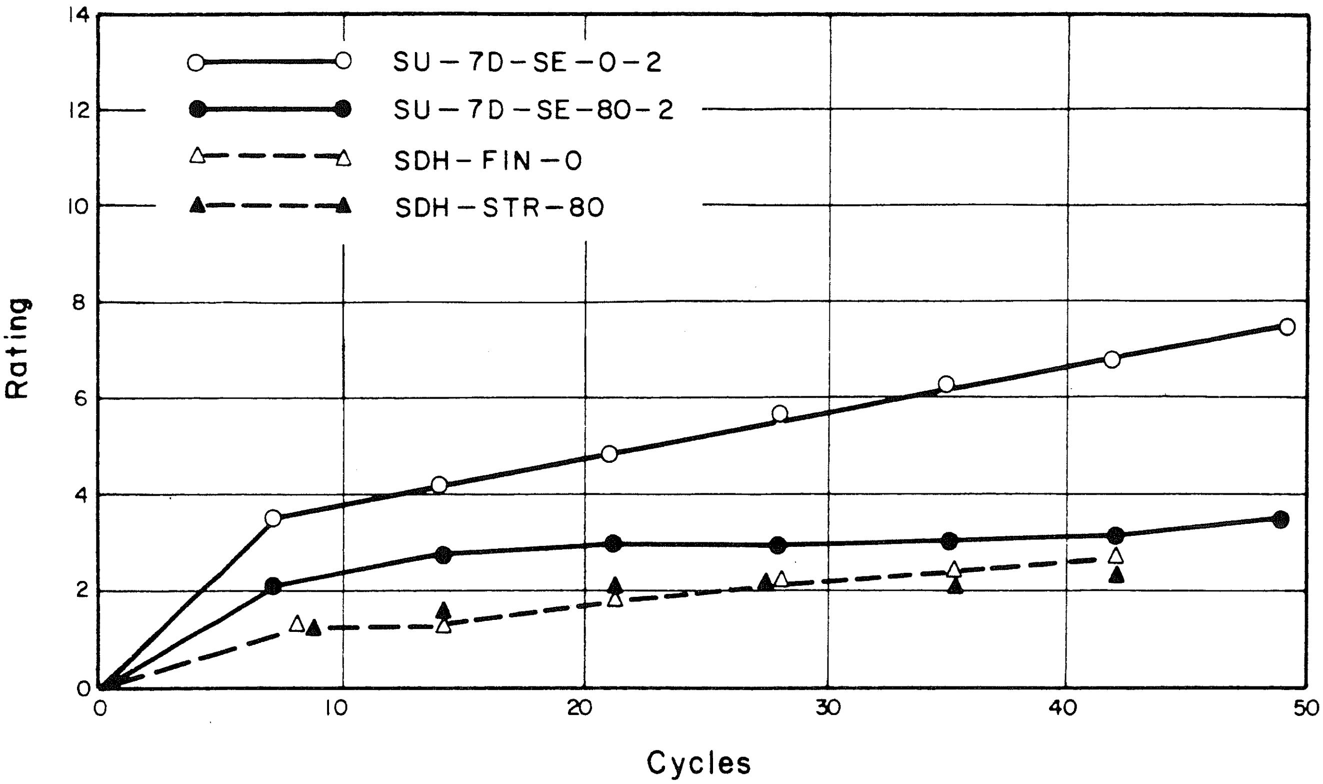


FIG. F63 INDIVIDUAL TEST RESULTS – SERIES 3D AND 4D – PHASE 3b

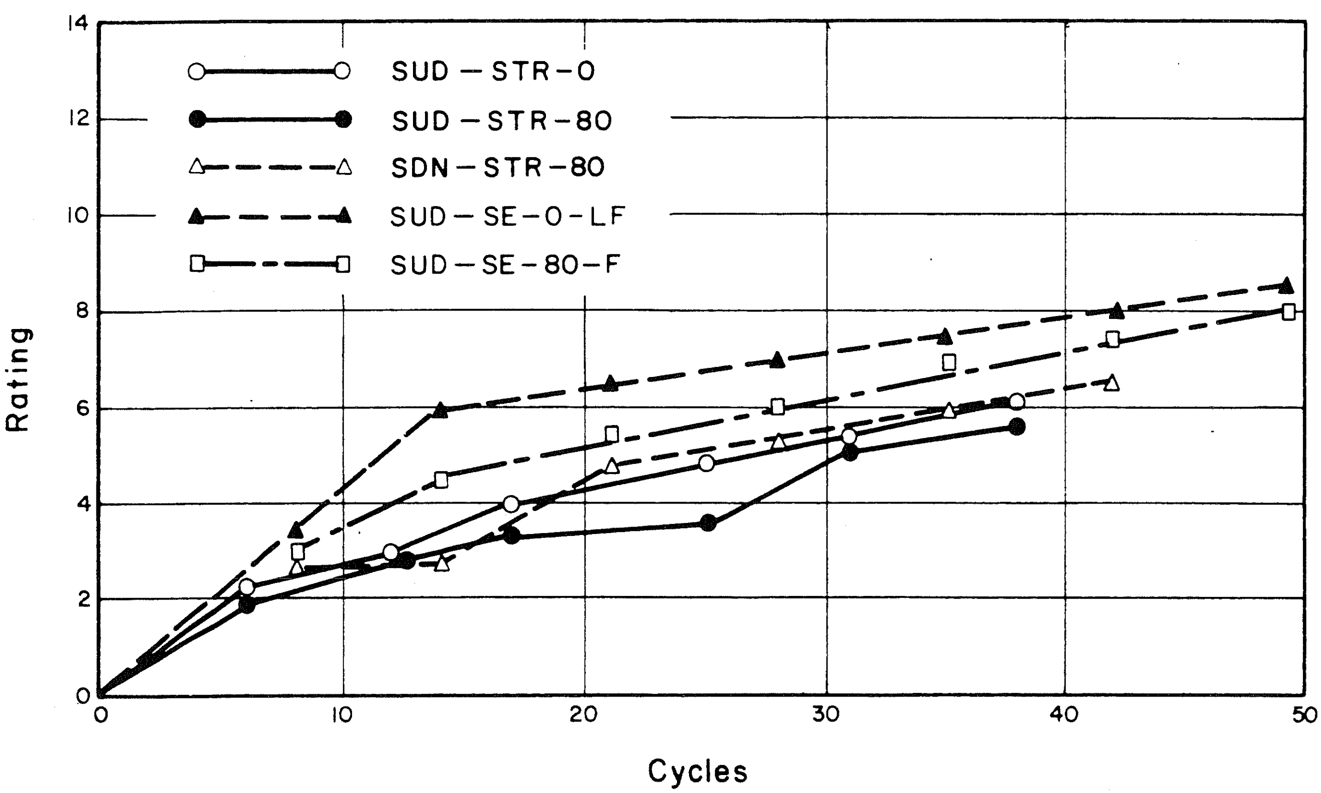


FIG. F64 INDIVIDUAL TEST RESULTS – SERIES 5D PHASE 3b

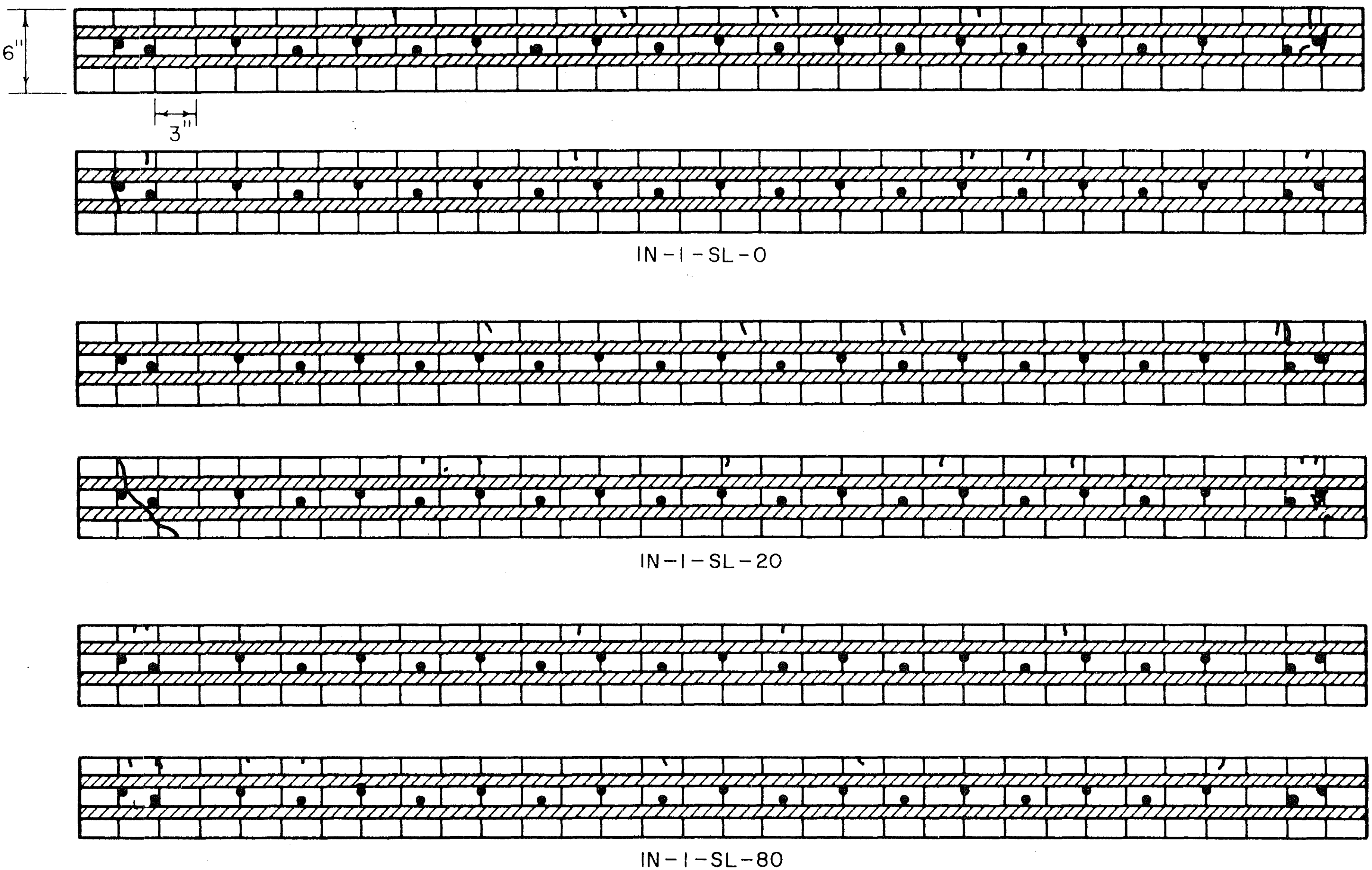


FIG. F65 CRACK PATTERN IN SPECIMENS— SERIES 1 — PHASE 2

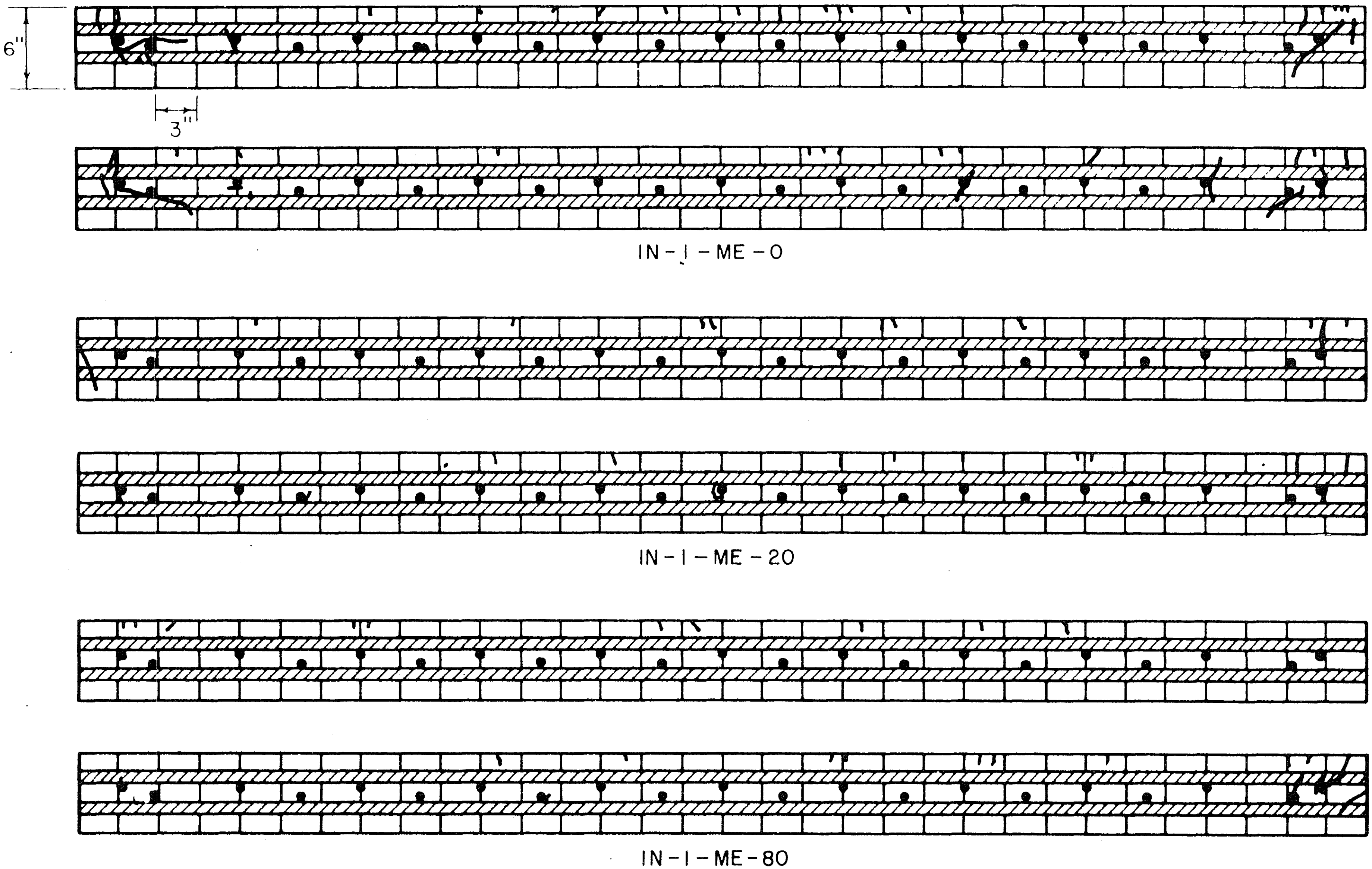


FIG. F66 CRACK PATTERN IN SPECIMENS — SERIES I — PHASE 2

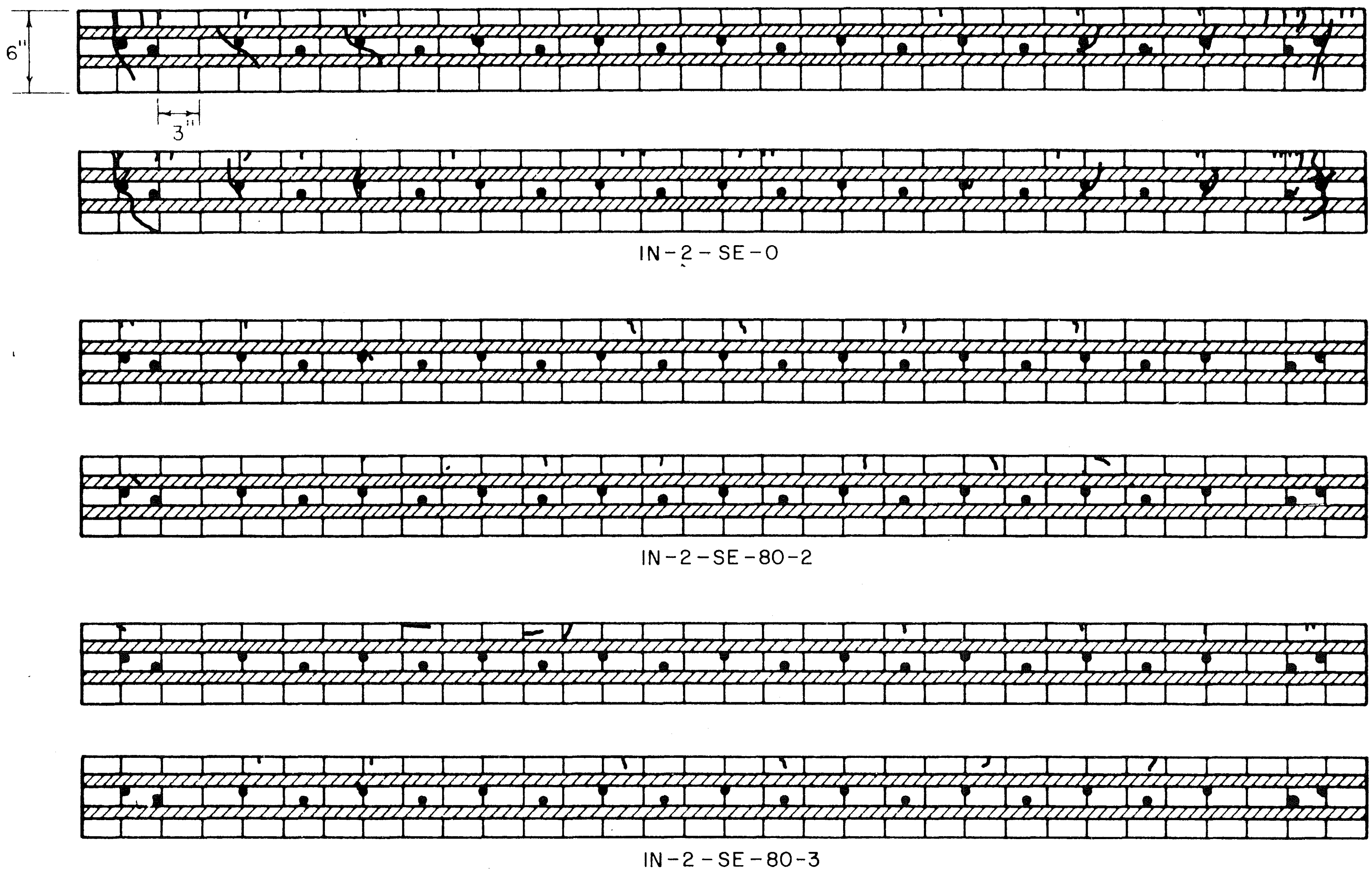


FIG. F 67 CRACK PATTERN IN SPECIMENS — SERIES 2 — PHASE 2

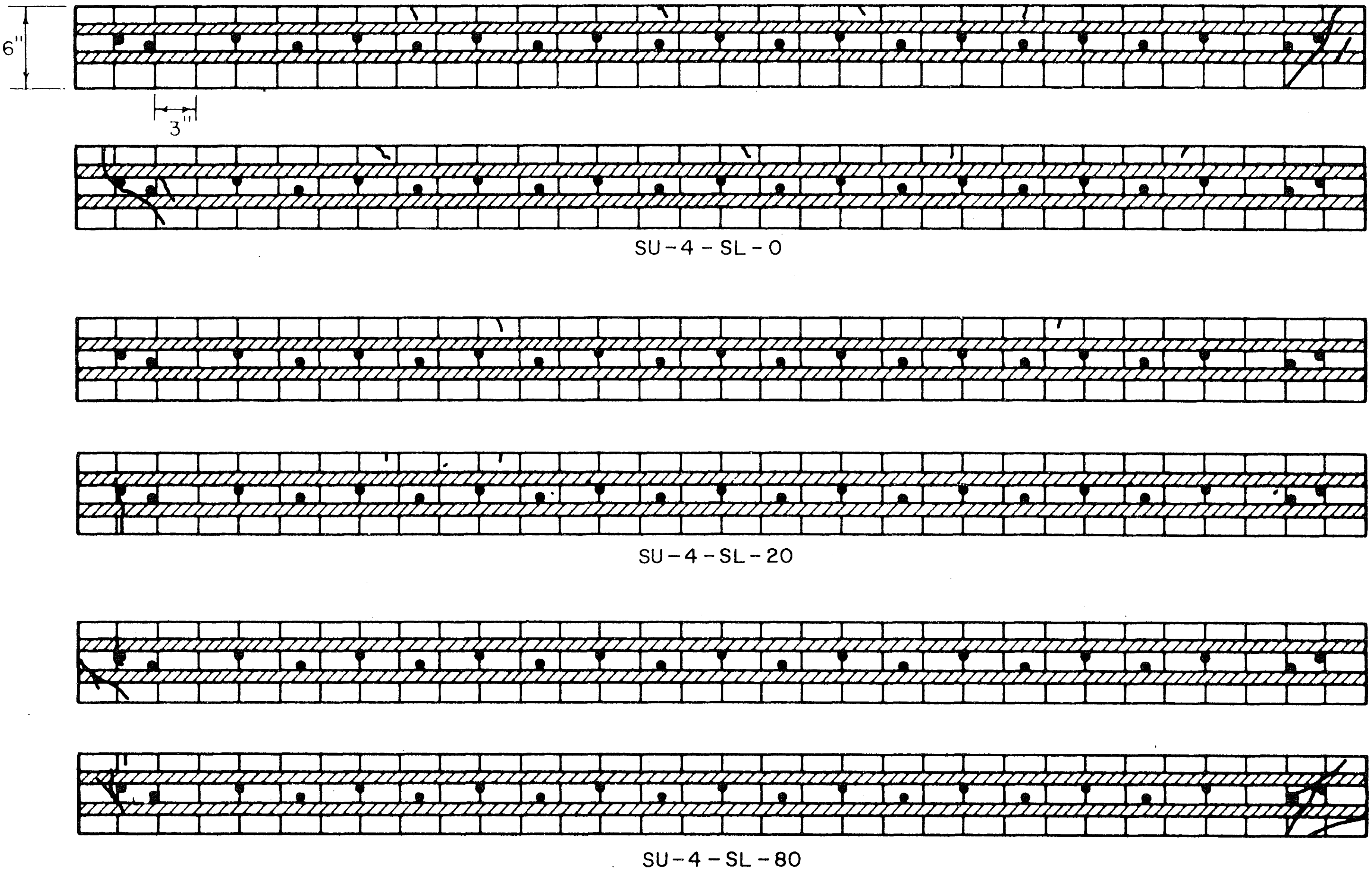


FIG. F68 CRACK PATTERN IN SPECIMENS-SERIES 4 — PHASE 2

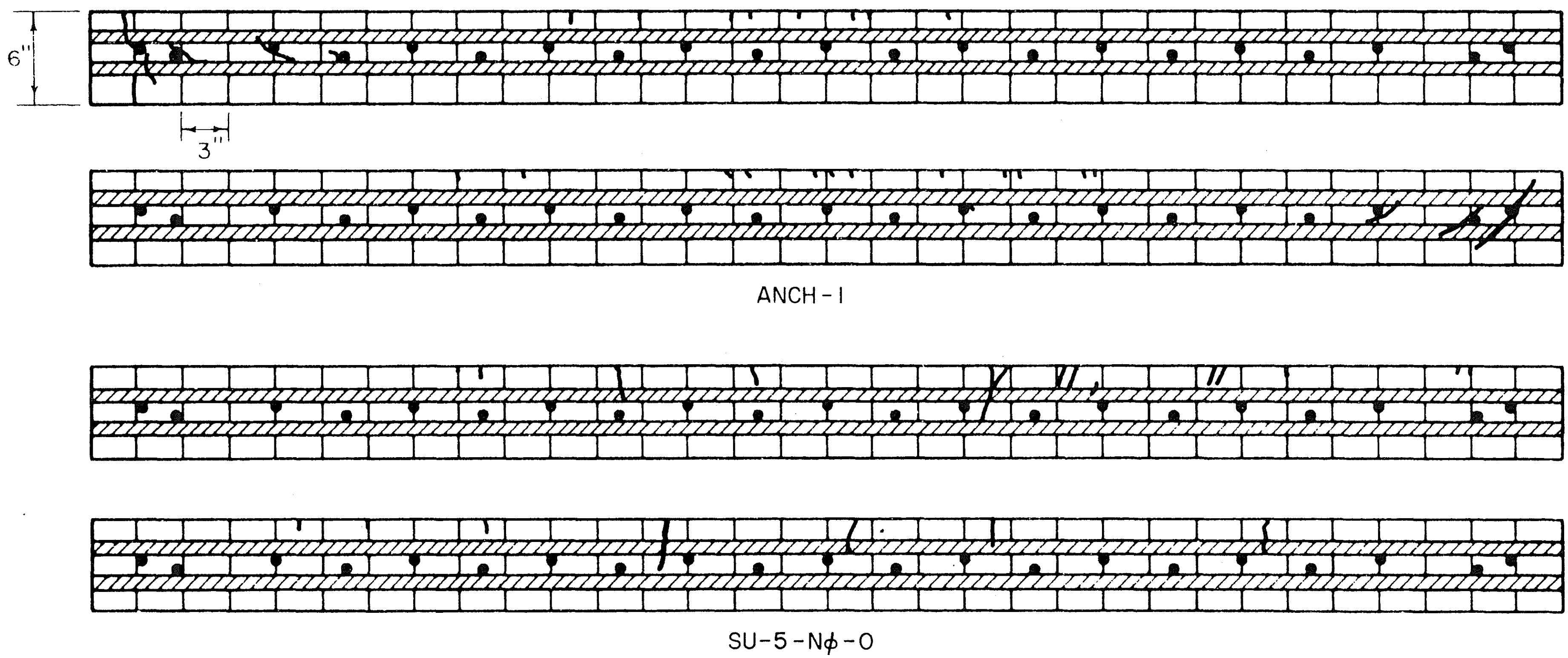


FIG. F69 CRACK PATTERN IN SPECIMENS WITH ANCHORED REINFORCEMENT – SERIES 5 – PHASE 2

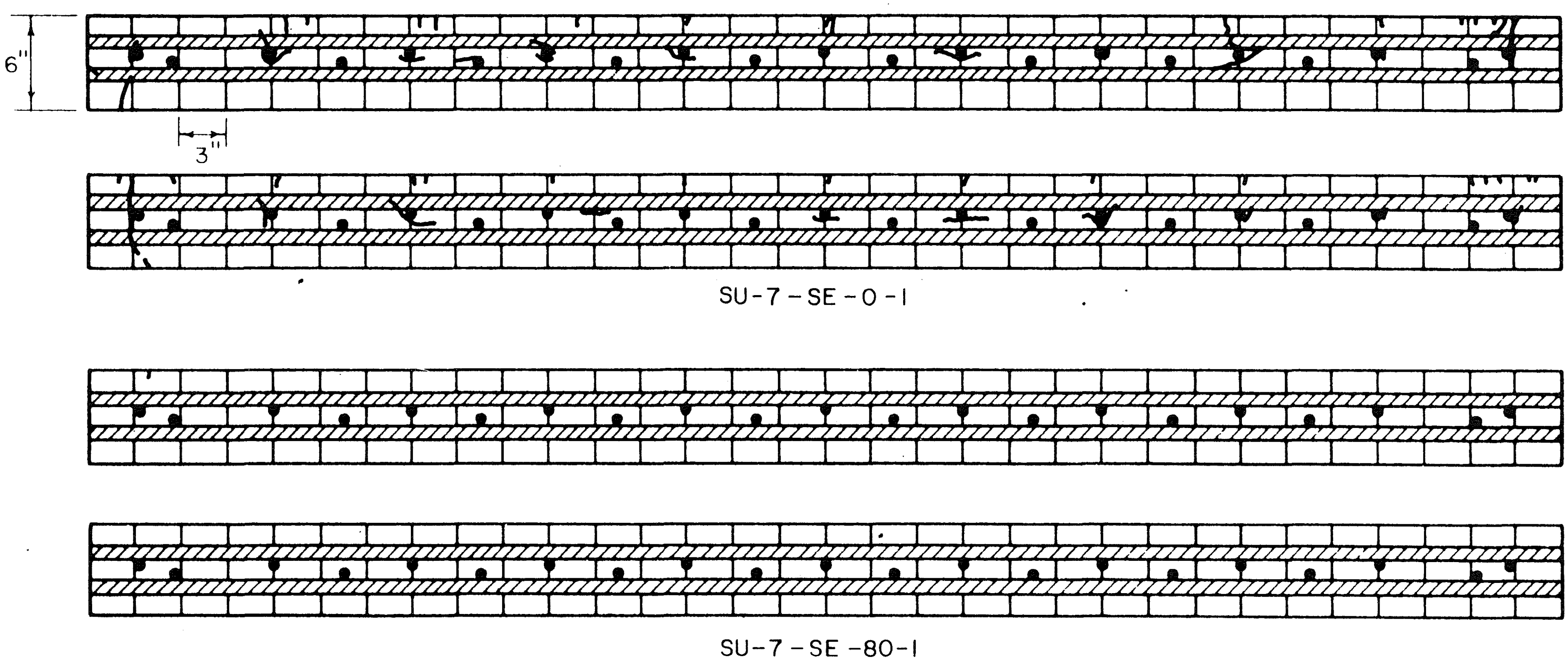


FIG. F70 CRACK PATTERN IN SPECIMENS — SERIES 7 — PHASE 2

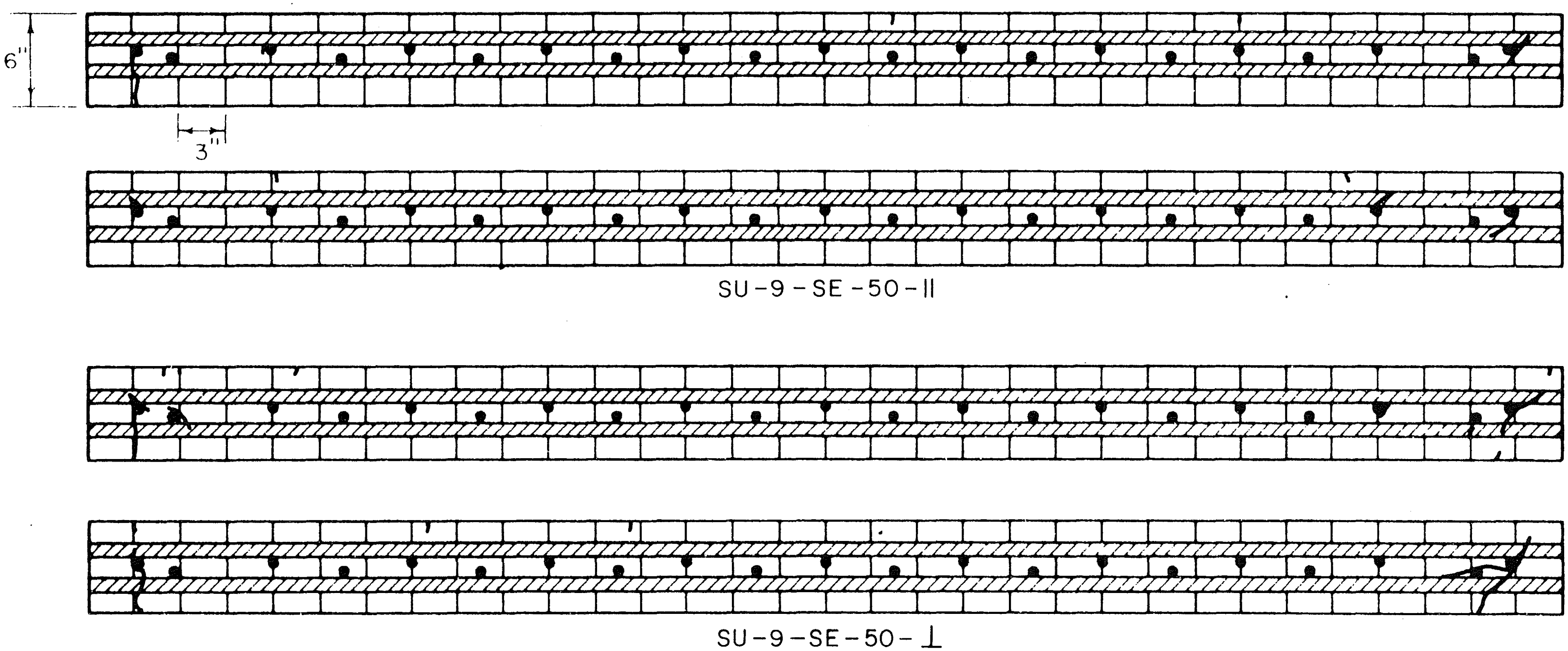


FIG. F71 CRACK PATTERN IN SPECIMENS — SERIES 9 — PHASE 2

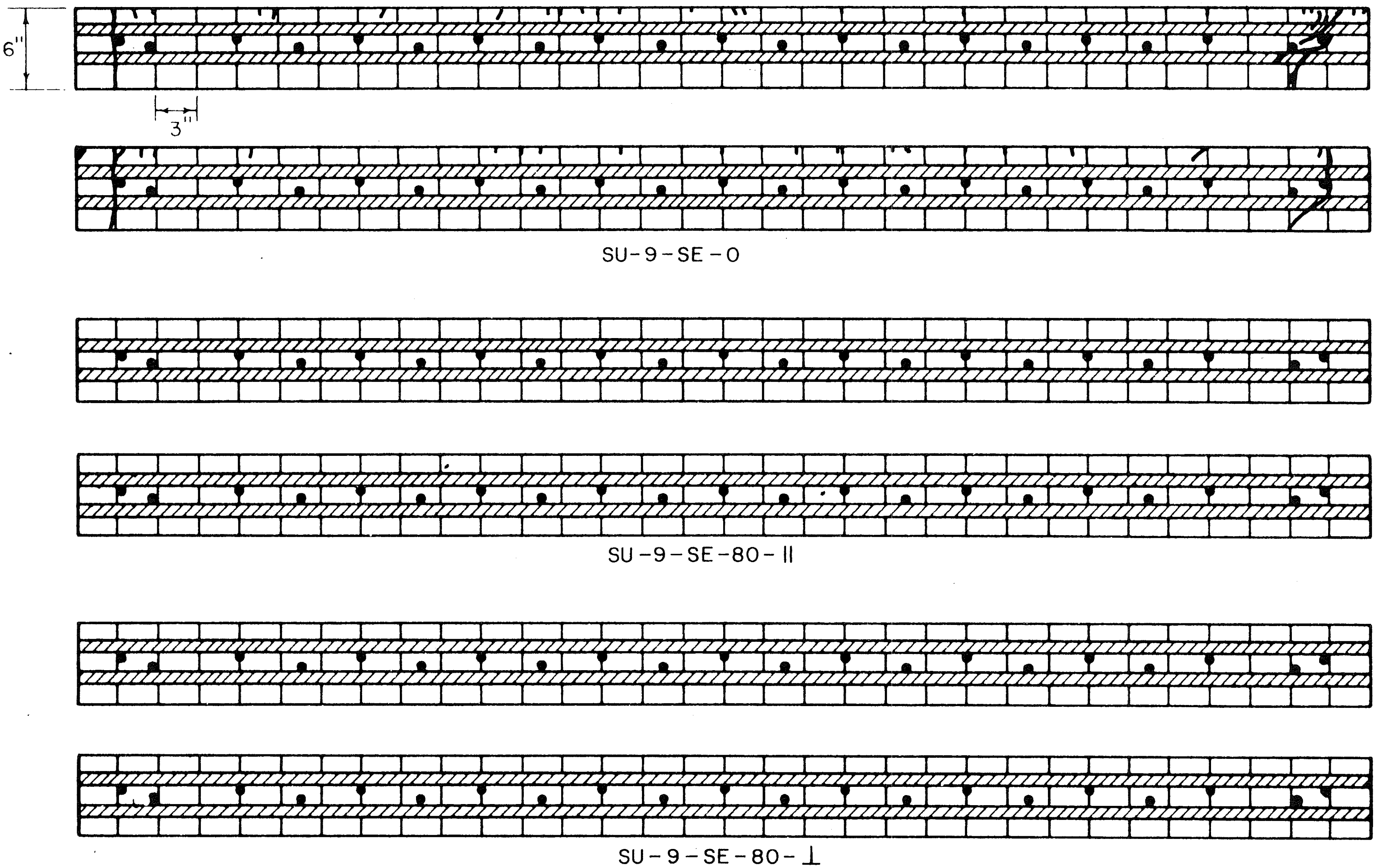


FIG. F 72 CRACK PATTERN IN SPECIMENS FROM SERIES 9-PHASE 2